STATIONARY RECIPROCATING ENGINES

Compliance Assistance Program
California Environmental Protection Agency
Air Resources Board

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100 INTRODUCTION

101 AIR RESOURCES BOARD

The California Air Resources Board (CARB or ARB) was created by the California Legislature to control air pollutant emissions and to improve air quality throughout the State. Under direction of the California Environmental Protection Agency (Cal/EPA), the ARB works closely with the United States Environmental Protection Agency (EPA) and local air pollution control districts in improving air quality in California.

The CARB:

- Conducts inspections to ensure compliance with air pollution regulations;

- Develops rules and regulations to assist local air pollution control districts in their efforts to maintain air quality standards;

- Establishes air quality standards which identify acceptable concentrations of specific pollutants which are intended to protect the health of vulnerable members of the general population and to prevent property and crop damage;

- Monitors air quality throughout the State; and

- Evaluates the effectiveness of pollutant control strategies both for automobiles and industrial sources.

102 COMPLIANCE ASSISTANCE PROGRAM

The Compliance Assistance Program (CAP), created in 1988 by the ARB, assists local air pollution control districts in conducting more comprehensive, consistent, and accurate facility compliance inspections. The CAP program also provides industry with information and tools, in the form of self-help publications, which clarify compliance requirements and help explain how to stay in compliance with air pollution rules and regulations. The CAP also assists industries in establishing their own compliance inspection programs. By conducting routine compliance inspections, industrial emissions sources can stay in compliance on a daily basis and can thereby avoid costly air pollution violations.

100 INTRODUCTION

Through the development and distribution of rule-specific publications, the CAP creates an effective flow of information in a variety of useful formats. Based on the idea that sources will comply if they can understand what is required of them, CAP publications identify regulation requirements and present them in more readily readable formats.

Publication formats include:

Handbooks. Easy to read, colorfully illustrated handbooks are developed for the industrial labor force and the interested public. Most can be read in ten minutes or less and most contain helpful self-inspection checklists.

Pamphlets. Quick reference pamphlets are filled with detailed flow charts, checklists and informative diagrams. These are designed for facility managers, plant personnel and industry's environmental managers.

Technical Manuals. Detailed technical inspection manuals are developed for local air pollution control district inspectors and industry's environmental managers. These contain rule information, process descriptions and step-by-step compliance inspection procedures.

In 1988 California enacted legislation known as the California Clean Air Act. This act requires the air pollution control districts to attain the State and federal ambient air quality standards at the earliest practicable date, and requires each air pollution control district to prepare a plan showing how it will achieve this.

Enforcement audits of certain industrial source types (such as solvent degreasers, gasoline vapor recovery systems, and coating of metal parts) show that noncompliance rates can be as high as 50 percent. Noncompliance results in excessive emissions.

Traditionally, ARB has sought to reduce noncompliance rates by providing an adequate deterrent through enforcement action against violators. In addition, ARB now seeks to reduce noncompliance rates and the associated excess emissions by ensuring that source operator knowledge includes:

- A basic understanding of the rules to which the source or product is subject; and

- A basic understanding of how compliance is to be determined.

If California's nonattainment areas are to have any chance of achieving the ambient air quality standards, the excess emissions resulting from noncompliance must be reduced with the help of both air pollution control inspectors and industry personnel. Air pollution control inspectors can identify problems for the source operator and propose corrective action, but their periodic visits cannot ensure continuous compliance. Compliance is the job of educated source operators. The goal of the Compliance Assistance Program is thus twofold:

CAP Goals

- To help air pollution control districts develop and maintain inspector knowledge; and

- To encourage industry to do self-inspections for continuous compliance.

102.1 TARGET AUDIENCE

This manual was written primarily for district field operation staff, district permitting staff, and environmental managers, but it may also be useful to other government agencies and industry personnel. It can be used as a reference manual or user's guide and it is designed for easy referencing, reading, and updating. It also contains graphics and illustrations to enhance understanding.

103 MANUAL SCOPE AND ORGANIZATION

After the introduction, this manual has a section on the theory and operation of stationary reciprocating engines. The basic theory, Otto cycle, main engine parts, and basic operation of the engines are discussed. The latter part of the Theory and Operation Section describes the power terms used for reciprocating engines. Following the Theory and Operation Section is the Emission Control Section, where the manual shows what pollutants are created by stationary reciprocating engines and how they are controlled. In the next section, Regulations, the manual describes the federal, state and district regulations that apply to reciprocating engines. After the Regulations Section, the Inspection Section describes how to inspect an engine to determine compliance with air pollution regulations. Where applicable, health effects and characteristics of pollutants are discussed. Appendix A includes a list of references used in preparing this manual; and, Appendix B includes applicable sections from the California Health and Safety Code. The Glossary contains important terms from the manual; the Index at the end of the manual provides easy access to information.

104 MAINTENANCE OF MANUAL

The Compliance Assistance Program welcomes your comments concerning this manual. Your comments and corrections, changes in legal requirements, and new information on equipment and processes will be collected and periodically distributed in an upgrade packet. Only the manual users who return the tracking card located in the very front of the manual will receive an upgrade packet, so be sure to fill out your card and send it in as soon as you receive the manual.

105 GENERAL DESCRIPTION

Internal Combustion Engine

Reciprocating engines, which are usually referred to as "internal combustion" engines, are a well known source of mechanical power for automobiles. These engines also have uses as stationary power plants. These engines will usually be called reciprocating engines in this manual, instead of internal combustion engines, since an internal combustion engine can also be a gas turbine or other type of engine. The term "internal combustion engines" in this manual means the reciprocating type.

An "external combustion" engine is an engine where the combustion takes place in one location and the heat energy from the combustion is transferred to another location before being converted to mechanical power. An example of an external combustion engine is a steam engine. In a steam engine a fuel is burned to boil water and make steam in a boiler. The steam can then be used to push a piston or turn a turbine. Energy that was released by the burning of the fuel is transferred to the steam and converted to mechanical power when it reaches the piston or turbine.

100 INTRODUCTION

Stationary Reciprocating Engines

In an internal combustion engine, fuel may be burned inside a cylinder with a piston. The energy from the rapid expansion of exhaust gases in the cylinder drives the piston; therefore, the energy from combustion is directly converted into mechanical energy. A major advantage of the internal combustion engine is that it is much smaller and lighter in weight than the external combustion engine.

In another variation, a gas turbine, fuel is burned in a combustor instead of a cylinder. Hot gases from combustion then expand through the turbine and force it to turn rapidly. The energy from combustion is again directly converted to mechanical energy to the shaft of the rotating turbine. The Compliance Assistance Program has prepared a Gas Turbines manual. In an internal combustion engine, no intermediate heat exchange equipment is required. A steam engine uses a boiler for heat exchange equipment and water for its working fluid.

106 RECIPROCATING ENGINE SIZES & APPLICATIONS

Four size categories are often used for stationary reciprocating engines: very small engines, small engines, medium bore engines and large bore engines. There is overlap between these groups, but they are more distinct when viewed on a horsepower-per-cylinder or displacement-per-cylinder basis.[1]

Very Small Engines

Very small engines generally have a bore size (cylinder diameter) ranging from 1.0 to 3.0 inches in diameter. They have a power ranging from 2 to 16 hp and run at high rotational speeds between 3,000 and 4,000 rpm (revolutions per minute). These engines are air cooled and are used on chain saws, recreation vehicles, small air compressors, small generators, lawn mowers, and other lawn and garden equipment. These engines usually have a single cylinder and often operate with a two stroke cycle (See Section 205.5). There are engines with cylinder diameters under 0.5 inches. These engines may be used for model aircraft, cars and boats.

Small Engines

Small bore engines generally have a bore size ranging between 3.0 and 5.0 inches in diameter. The power output ranges between 3.0 and 50 hp and their rotational speeds are between 1,000 and 4,000 rpm, so these engines are known as low power high speed engines. Some applications of small bore engines are power for refrigeration compressors in railroad cars and trucks, and hydraulic pumps for trash compactors and dump trucks. They are often used for electrical power generation in remote locations. These engines may have one or two cylinders, but some may have as many as four cylinders. They usually operate on a four stroke cycle using gasoline or diesel fuel.

Medium-Bore Engines

Medium-bore engines have a bore size ranging between 3.5 and 9.0 inches in diameter and a power output of 50 to 1,200 hp. These engines are regarded as high speed engines, since they have a rotational speed between 1,000 and 4,000 rpm. They have multiple cylinders and are powered with gasoline, diesel, or even natural gas. The applications of these engines include various agricultural uses (i.e. water pumps), nonpropulsive marine applications and miscellaneous industrial applications.

Large-Bore Engines

Large-bore engines have bore sizes that range between 8.0 and 18.0 inches in diameter and a power output between 400 and 13,000 hp. The rotational speed of these engines is between 250 and 1,200 rpm, which is much lower than the other classes of smaller engines. Large-bore diesel engines usually operate on a four stroke cycle, but these engines may operate on a two stroke cycle. The diesel engines may also burn a combination of diesel fuel and natural gas, but the spark ignition engine typically uses just natural gas.

Large bore engines are more economical than medium bore engines since they have a lower fuel consumption and a longer life. Because of these advantages they are often used in applications requiring continuous operation, such as electrical power generation, natural gas production and transport, and oil field production and exploration.

106.1 STATIONARY RECIPROCATING ENGINE APPLICATIONS

Power & Emergency Power Generation

1. Electric power generation and backup or emergency power - Stationary reciprocating engines can be used to turn generators to create electricity. They may also be used for backup power in case the normal source of electricity from a utility is disrupted (Fig. 106.1). These are often found in hospitals and businesses that require a very trustworthy source of power.

Cogeneration

2. Cogeneration - Energy may be recovered from very large engines for hot water or steam for other processes. Waste gases can be used as fuel for reciprocating engines. Also see the Landfill Gas Control Facilities and the Boilers Compliance Assistance Technical Manuals for additional information on Cogeneration.

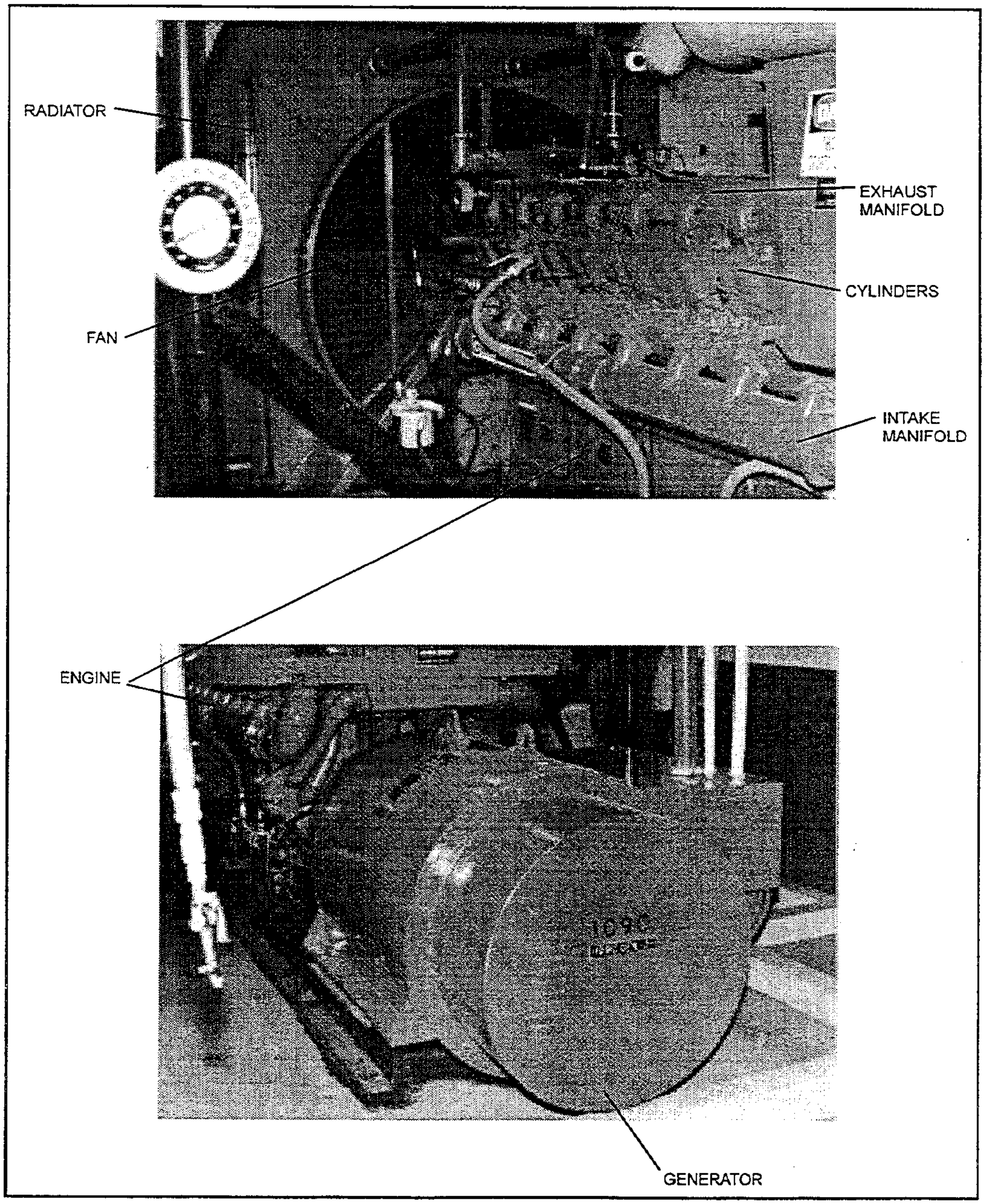

Figure 106.1 Reciprocating Engine with Generator

Industrial Processes

3. Industrial processes - The power produced by reciprocating engines can be used for a variety of industrial processes. A few examples include: compression and transport of natural gas, operation of drilling rigs, mud pumping for drilling rigs and water pumps for agriculture, municipal water supplies and firefighting.

200 THEORY & OPERATION

After presenting a brief history of reciprocating engines, the theory and operation of them will be discussed. The engine theory discussion includes a brief description of units and properties involved in thermodynamics, and a description of the Otto and Diesel cycles which provide the basis for reciprocating engine design and operation. The section on engine operation includes a description of the main parts found in most engines. Toward the end of this section power terms will be described.

201 HISTORY OF THE RECIPROCATING INTERNAL COMBUSTION ENGINE

Many developments from different inventors led to the modern engine and a complete history would fill an entire book. Only a brief description of the major events in the development of engines will be discussed.

Leonardo da Vinci

Fire Engine

The earliest developments leading to the creation of the internal combustion engine date back to the Renaissance period. Early engines used gunpowder and the invention of the cannon is considered to be the beginning of the internal combustion engine.[1] In 1508, Leonardo da Vinci sketched the "fire engine," which was a device for "raising a heavy weight by fire." The sketch had a vessel serving as a cylinder and a piston with leather for sealing. It is thought that Leonardo da Vinci may have wanted to use gunpowder to ignite a charge for the device. Although the device was never built, it is estimated that it could have raised a 1600 kg weight a distance of 3 m with 0.22 kg of gunpowder.[2]

Christian Huygens

Gunpowder Engines

In 1673, a dutch physicist named Christian Huygens built several gunpowder engines. He developed the first working piston in a cylinder using heat. His most popular engine had a cylinder made of tin-plated sheet metal lined with a thick layer of plaster. The piston was sealed by leather and there were two ports near the top of the cylinder with wetted, flexible leather hoses. When a gun powder charge at the bottom of the cylinder was ignited the piston moved to the top of the cylinder and uncovered the ports allowing exhaust gases to exit. The cooling of residue gases caused a vacuum forcing the piston to move back down. A rope connected to the piston could then raise a weight.

Denis Papin

Denis Papin (1647-1712?) was a gifted assistant of Christian Huygens. He developed his own gunpowder engines which had improved designs, but they were really no more effective than Huygens' engine.

200 THEORY & OPERATION

Papin made large contributions from his work with steam. He was the first person to use the power of steam in a cylinder to move a piston. He experimented with a device that included a rod and piston fitted into a 2.5 inch diameter tube. He used a fire to heat water in the tube and create steam which caused the piston to rise. The piston was then latched at the end of its stroke. A vacuum was then formed by cooling the tube. The piston was then unlatched, allowing it to return to its original position.

Attempts were made using gunpowder for fueling engines until the first half of the 19th century, but in the 18th century, after Papin's developments, most engine research and development was concentrated in steam engines. Gunpowder was increasingly seen as too dangerous as a fuel for engines.

Thomas Newcomen

The first reliable steam engine was developed by Thomas Newcomen (1663-1729). His engines were used to draw water from mines. As with earlier engines, he used wetted leather for sealing between the piston and cylinder. His Dudley Castle engine was able to raise ten gallons of water over 150 feet on each stroke of the engine.

James Watt Steam Engine

James Watt (1736-1819) was a brilliant Scotsman who transformed the crude steam engine of Newcomen into a much more versatile engine. He developed a condenser for the mine pump which immediately doubled its efficiency. He did a large amount of work to advance thermodynamics. He made large advancements to the control, instrumentation and design of steam engines. The unit for the measurement of power output, the horsepower, was developed by Watt.

Henry Wood

Sir George Cayley Air Engine

The first person to propose moving away from using steam to operate engines was Henry Wood (1715-1795). He envisioned pumping hot air from a furnace into a cylinder and then cooling the air to allow the atmosphere to push a piston on the inward stroke as in the Newcomen engine. In 1807 Sir George Cayley was the first person to develop an "air engine" or "furnace gas" engine working on the principles proposed by Wood.[3]

Robert Stirling John Ericsson

Robert Stirling (1790-1878) and John Ericsson (1803-1889) contributed much to the development of air engines. In 1816 Stirling developed an air engine and regenerator that was one of the most amazing inventions in the history of heat and power. The theory of the operation of the Stirling engine is very complicated even with modern thermodynamics. The original engine had a cylinder diameter of two feet and a length of ten feet and produced about two horsepower.[4] John Ericsson was a Swedish engineer who produced many air engines. Although his engines were inefficient and noisy compared to the design developed by Stirling, they were reliable and easy to operate. He also designed the Civil War iron clad, the U.S.S. Monitor.[5]

By 1870 thousands of air engines had been developed. They were generally safe and reliable and the well designed ones consumed less fuel than steam engines. On the other hand, they were heavy and suffered short operating lives due to cracking and burning of the pistons from excessive heat. Air engines were obsolete by the early 1900's.

Industrial Revolution

The Industrial Revolution contributed a lot to the development of the internal combustion engine and the increased use of petroleum products in the late 1800's helped increase the use of petroleum as a fuel for engines. At that time, petroleum was mainly used as a lubricant. Steam engines were primarily used for the drilling and pumping necessary for oil field production. Because of the increasing costs of using steam, the necessity of water for steam engines, and corrosion of boilers from hard water, some designers began using wellhead gas (natural gas) to fuel engines. At that time wellhead gas was a waste product.

Nicolaus Otto

Four Stroke Engine

Otto Cycle

A major development in the history of the internal combustion engine was the creation of the four stroke engine which many engines use today. Nicolaus Otto, a German salesman, originally demonstrated an engine operating on a four stroke cycle in 1876, but the four stroke cycle was originally developed by a Frenchman named Beau de Rochas in 1862. Rochas attempted to publish a patent for his work but failed to pay the required fees at that time. Other engine manufacturers filed suit to invalidate Otto's patented engine. The four stroke cycle is also called the "Otto Cycle" but text books sometimes refer to Otto's engine operating on the "Beau de Rochas cycle."

Jean Joseph Etienne Lenoir

Atmospheric Engine

In 1860 Otto started experimenting with an engine developed by Jean Joseph Etienne Lenoir. He then developed and marketed an "atmospheric engine," before his four stroke engine, that used explosive combustion to drive a piston vertically upward and the cooling of exhaust gases for the return stroke downward. Otto's four stroke engine had a bore of 6.3 inches and a stroke of 11.8 inches. It used slide valves similar to those on a steam locomotive engine and developed 3 horsepower. It had an efficiency of 14% which was two to three times the efficiency of comparable steam engines.

202 SUBSTANCE PROPERTIES AND BASIC UNITS

This section is an introduction to the description of the thermodynamic cycles with which Otto (Section 203) and diesel (Section 204) engines operate.

Mass
In English units, the unit for mass is the pound-mass (lbm). From Newton's law:
$F = (m/g_c)a$
where:
F = force (lbf)
m = mass (lbm)
g_c = gravitational constant 32.2 (lbm-ft)/(lbf-sec^2)
a = acceleration due to gravity 32.2 ft/sec^2.

From the above equation, the difference between pounds (lbs.), which is more accurately termed as pounds-force (lbf) in fields of air pollution, science and engineering, and mass (lbm) can be seen. Although (lbm) and (lbf or lbs) will be the same numerically because the two 32.2's cancel, they have different units.

Pressure
Pressure is usually measured by pounds per square inch (psi) or pounds per square foot (psf). Other units include atmospheres (1 atm = 14.7 psi), inches of water (1 atm = 407.1 inches of water), torr (1 atm = 760 torr), millimeters or inches of mercury (1 atm = 760 millimeters of mercury) and millibars.

Gage pressure is the pressure relative to atmospheric pressure. Atmospheric pressure is 14.7 psi, so a device measuring gage pressure would not count this pressure. The pressure measured by a tire gauge, for example, is gage pressure and a gage pressure reading is typically noted as "psig" (the "g" stands for gage). An absolute pressure reading includes atmospheric pressure and it is typically noted as "psia" (the "a" stands for absolute). A tire gauge pressure reading of 10 psig would therefore be equivalent to 14.7 + 10 = 24.7 psia.

Standard Temperature and Pressure (STP)

Standard Temperature and Pressure (STP) is used to standardize the pressure and temperature of systems. STP is defined as one atmosphere at 32, 60, 68, or 70 degrees Fahrenheit. STP makes it easier to accurately compare parameters for gases between different systems, such as flow rates.

Temperature
The temperature of a substance is a thermodynamic property that depends on the substance's energy content.[6] Heat energy flows from a hot object to a cold one.

The units of temperature are Fahrenheit in the English system and Celsius in the SI system. The absolute temperature scale should be used for calculations unless a temperature difference is required. In the English system the Rankine scale is used. Absolute zero is zero degrees Rankine (-459.67 degrees Fahrenheit), and zero degrees Kelvin (-273.15 degrees Celsius).

Density and Specific Volume
Density (ρ) is mass per unit volume - i.e. lbm/ft^3. Specific volume (v) is simply the reciprocal of density ($v=1/\rho$).

Internal Energy
Internal energy (U of u) is all of the potential and kinetic energy possessed by a substance. Internal energy is a function of temperature. As the temperature of a system increases the internal energy increases. Internal energy is usually in Btu/lbm or Btu/lb-mole, where "u" indicates Btu/lbm and "U" indicates Btu/lb-mole. The term Btu (British Thermal Unit) is the amount of energy required to raise one pound of water one degree Fahrenheit. It is approximately equivalent to energy released from burning a wooden match.

British Thermal Unit (Btu)

Enthalpy
Enthalpy (H or h) is a property that represents the total useful energy in a substance.[7] These substances often include steam or hot air. Enthalpy consists of two parts, internal energy and flow energy.

$h = u + pv/J$ (Btu/lbm)

$H = U + pV/J$ (Btu/lb-mole)

V = volume (ft^3)
v = specific volume (ft^3/lbm)
J = Joule's constant (778 ft-lbf/Btu)
U and u = internal energy (Btu/lb-mole and Btu/lbm, respectively)
p = pressure (lbf/ft^2)

The "pv or pV" term is the flow energy.

Entropy
Entropy (S or s) is the amount of energy that is no longer available to do work. It also characterizes the disorder or randomness of a system.

Specific Heat
Different substances require different amounts of heat to attain a specific change in temperature. The ratio between the heat and the temperature change is the specific heat.[8]

$c = Q/(m\Delta T)$ (Btu/lbm-°R)
where:
m = mass (lbm)
Q or q = heat transfer (Btu) or (Btu/lbm)
ΔT = temperature change
c or C = specific heat (Btu/lbm-°R) or (Btu/lb-mole-°R)

The Otto cycle is one of the air standard cycles (power cycles that include the Brayton cycle for gas turbines and the diesel cycle) and the working fluid is air, but the specific heat of gases depends on its conditions. The specific heats used to identify gases are constant volume (c_v) and constant pressure (c_p) specific heats.

Therefore for gases:
$Q = mc_v\Delta T$ (constant volume process) and
$Q = mc_p\Delta T$ (constant pressure process)

The ratio of the specific heats for gases is defined as "k."
$k = c_p/c_v$
"k" for air is typically 1.4.

203 THE OTTO CYCLE

The theoretical cycle for the spark ignited reciprocating engine is the air standard Otto cycle. The cycle is named after a German, Nicolaus Otto, who developed an engine based on principles outlined by a Frenchman named Beau de Tochas. The Otto cycle is really not a cycle, because exhaust exits the engine and the air used by the engine is not continually recirculated through it.

The Otto cycle consists of four events within a piston and cylinder (Fig. 203.1)[9] From "a" to 1 is the intake stroke, where the piston moves down the cylinder and draws in a fresh mixture of fuel and air through the intake valve. From 1 to 2 the air/fuel mixture is compressed by the piston moving back up the cylinder. Under theoretically ideal conditions this compression is an isentropic (no entropy change) compression. The entropy (energy not available to do work or the disorder or randomness of a system) from 1 to 2 is constant, but the piston moves from the bottom of its travel (bottom dead center) to the top of its travel (top dead center). From the "P-V" diagram (pressure in the cylinder vs. volume of the air in the cylinder), during the compression the volume in the cylinder decreases and the pressure increases.

From 2 to 3, the compressed air/fuel mixture is ignited by the spark plug. This process is called "constant volume heat addition" in the ideal cycle, since the piston is at the top of the stroke and the combustion of the mixture creates a release of energy. From 3 to 4, hot gases push the piston down the cylinder and the piston moves from the top dead center to bottom dead center. Ideally, the expansion of the volume in the cylinder is an isentropic expansion. During the process from 4 to 1, the piston is at the bottom of the stroke, and heat is rejected by constant volume heat rejection.

The Otto cycle is normally illustrated as 1-2-3-4-1. In most P-V diagrams in thermodynamic books, the exhaust stroke from 1 to "a" are not shown, since the effects of the two processes in the ideal cycle cancel each other so that there is no loss or gain in heat or work. From 1 to "a" the piston moves back up the cylinder, but the exhaust valve opens, so exhaust is removed from the engine. From "a" to 1, fresh air is drawn into the cylinder as the piston moves from the top of the cylinder to the bottom. The cycle then repeats, starting with another compression cycle from 1 to 2. Many thermodynamic books use specific volume instead of volume to illustrate the Otto cycle. Specific volume is the inverse of the air density (volume of the air divided by the mass of air in the cylinder).

Some thermodynamic relationships for the Otto cycle include:

Compression Ratio

$R = V_1/V_2 = V_4/V_3$

where:

R = Compression ratio

V = Cylinder volume

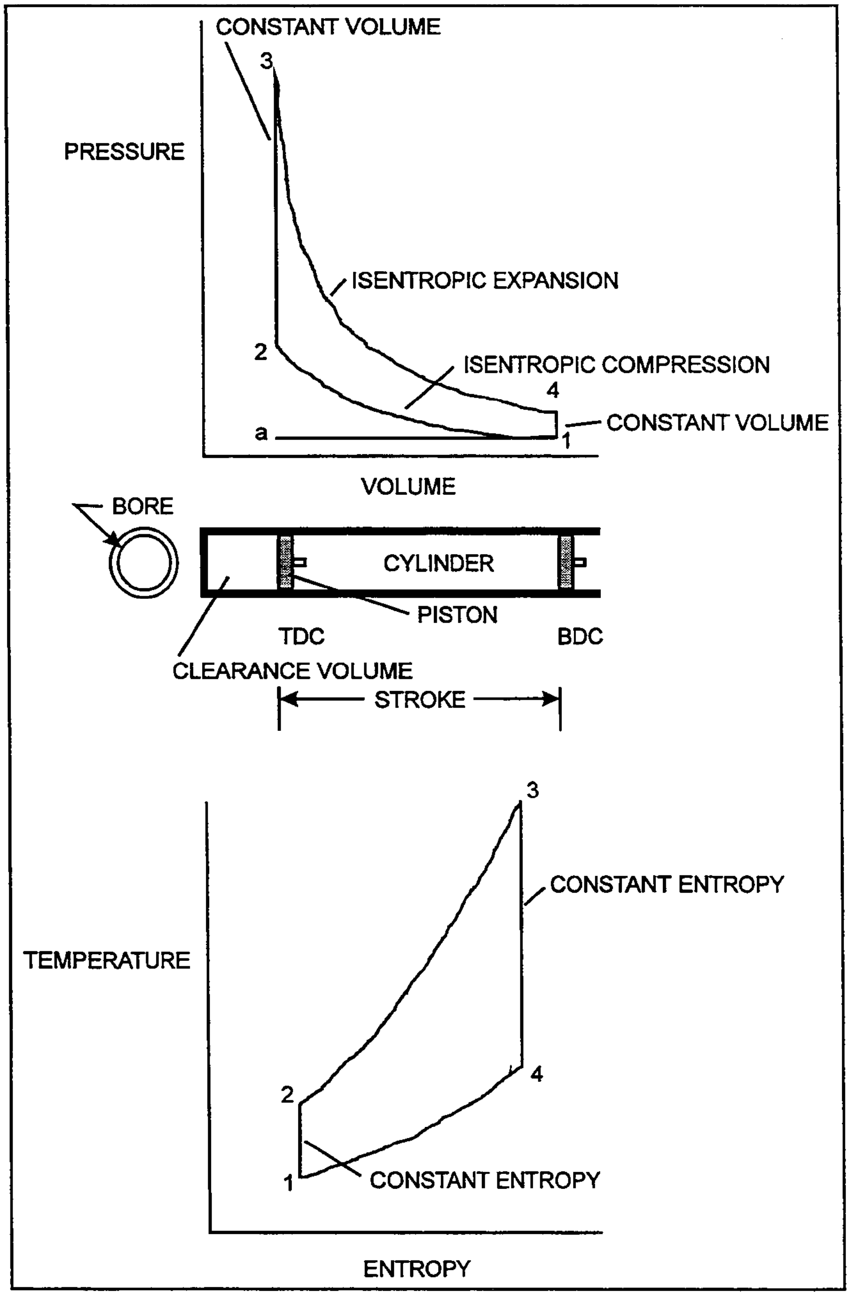

Figure 203.1 Ideal Otto Cycle

$T_4/T_3 = T_1/T_2$
T = Temperature (absolute)
$Qin = c_v(T_3 - T_2)$
$Qout = c_v(T_4 - T_1)$
where:
Qin = Heat released into cylinder
c_v = Constant volume specific heat
Qout = Heat rejected into atmosphere

$Wout = c_v(T_3 - T_4)$
$Win = c_v(T_2 - T_1)$
where:
Wout = Work output by piston
Win = Work input by piston for compression

$\eta_{th} = (Qin - Qout)/Qin = (Wout - Win)/Qin = 1 - 1/R^{k-1}$
where:
η_{th} = Thermal efficiency

203.1 THE ACTUAL CYCLE

The actual cycle for the spark ignition engine is illustrated in Figure 203.2. In the P-V diagram, note how it has a smaller area than the ideal cycle. The reduced area of the cycle shows the reduced work output, since the area of the cycle (pressure times volume) is equivalent to units of work (lbf-ft). The actual cycle efficiency of an engine will be about 50% of the air standard Otto cycle.

The main reasons that the actual cycle differs from the air standard Otto cycle are: [10]

1. Specific Heats - Within the temperature ranges of the actual cycle and the ideal Otto cycle the combustion products in the actual cycle have a higher specific heat. The maximum temperature of the actual cycle and the ratio of the specific heats (k) will also be lower, resulting in a lower work output for the actual cycle.

2. Dissociation - In the actual cycle, because of the high temperatures involved, the compounds in the exhaust will tend to dissociate, or break up into other compounds such as carbon monoxide (CO), hydrogen H_2, and oxygen O_2 in an

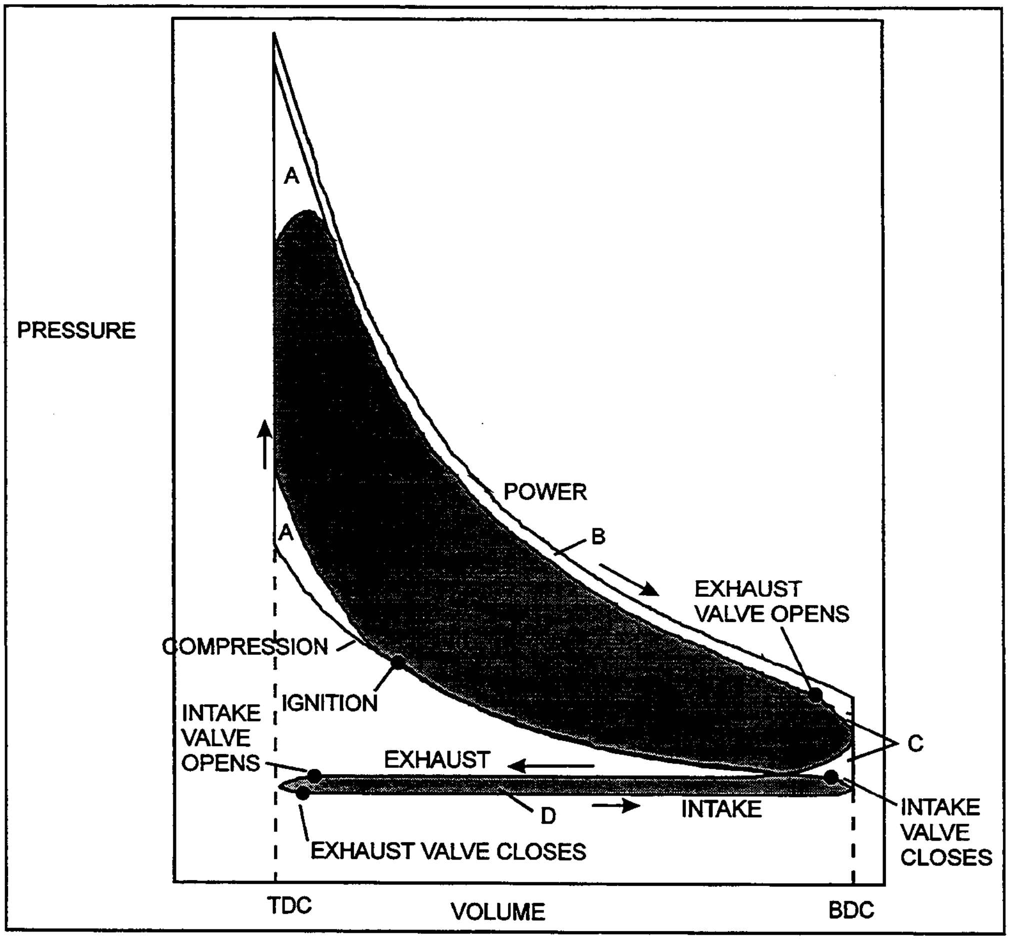

Figure 203.2 Actual P-V Diagram (Indicator Card)
Spark Ignition Engine

endothermic reaction. This results in less energy available to do work and a reduction in efficiency.

3. Non-instantaneous burning - In the air standard cycle the addition of heat is from combustion and is assumed to be instantaneous, but in an actual operating engine the combustion takes a period of time to occur (Area A).

4. Heat losses - The ideal cycle assumes there are no heat losses, but in the actual cycle there are heat transfer losses through the cylinder and other areas (Area B).

5. Exhaust gas effect - In the actual cycle all of the combustion products are not removed from the cylinder during the exhaust stroke. This is especially due to the clearance volume, or squish gap, that remains when the piston reaches the top of its travel. The exhaust gases dilute and heat the next fresh charge of fuel and air. This also reduces the mass of fuel and air admitted to the cylinder, resulting in a reduction of the work output of the cycle.

6. Valve timing and blown-down losses - As with instantaneous burning, in the ideal cycle instantaneous rejection of heat was assumed. In a real-world actual engine, it is not possible to instantaneously reject the heat and exhaust. Furthermore, in an actual engine the exhaust valves open before the piston reaches bottom dead center. This causes an additional loss in output (Area C).

7. Pumping loop - In the actual cycle the pressure in the cylinder during the intake stroke is different than the pressure during the exhaust stroke. This produces a "negative" area loop on the P-V diagram (Area D). This negative energy is due to the pumping action that the piston must perform.

The P-V diagram from an actual operating spark ignition engine is also called the indicator diagram or indicator card (Fig. 203.2).[11] It is an actual record of the pressure in the cylinder when the piston is at different positions during the cycle and therefore when there are different volumes in the cylinder. The shape of the indicator card also helps show how well an engine is operating. Instruments for recording the indicator card may also be called engine indicators.

Unlike the ideal cycle, ignition occurs before top dead center in an actual engine, since it takes time for the air and fuel mixture to burn. The exhaust valve also opens early, since it takes time to open the valve. The energy required to pump exhaust gases out of the cylinder is indicated by the loop "D."

204 THE AIR STANDARD DIESEL CYCLE

Rudolph Diesel

Compression Ignition Engine

The Diesel cycle, which was developed by a German named Rudolph Diesel in 1892, is the theoretical cycle for the diesel or compression ignition engine. The cycle is very similar to the Otto cycle, but the main difference with the diesel cycle is that it uses the heat of compression for ignition so there are no spark plugs. In the Diesel cycle heat is supplied at constant pressure, while in the Otto cycle heat is supplied at constant volume. The parts of the ideal cycle are

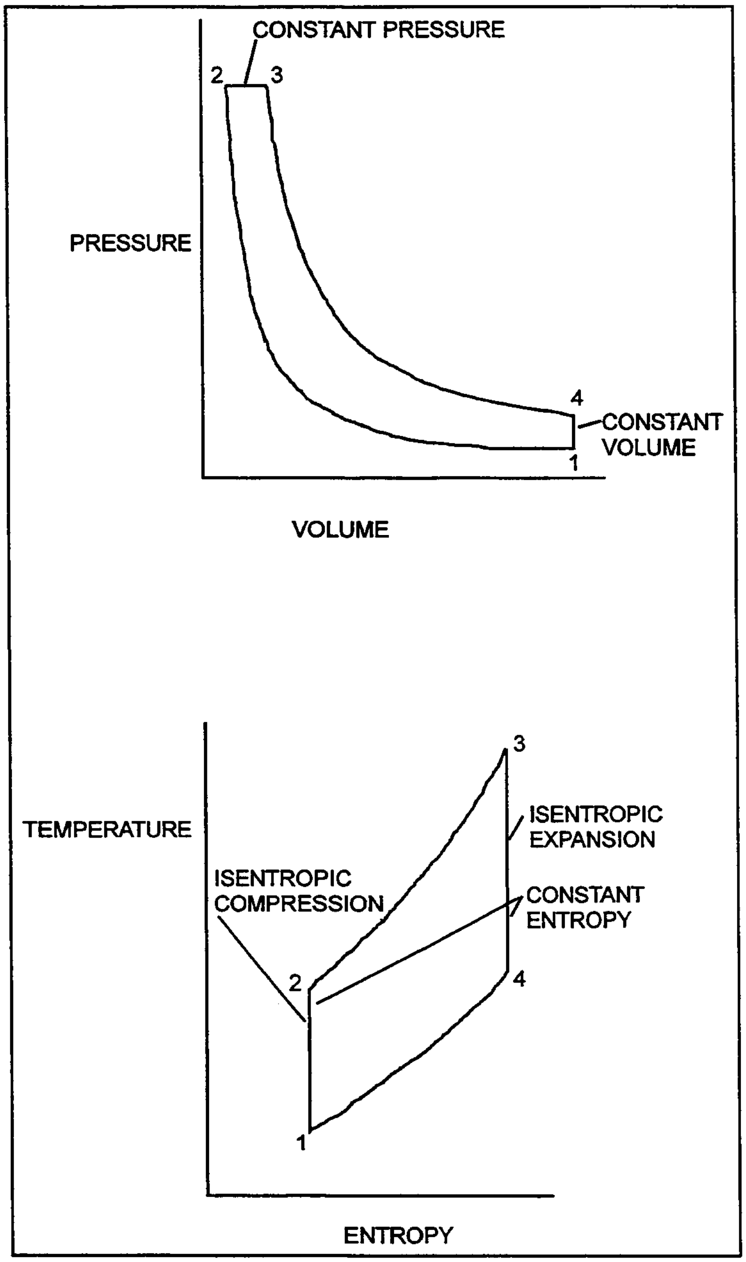

Figure 204.1 Air Standard Diesel Cycle

isentropic (no energy loss) compression of the air by the piston from 1 to 2 (Fig. 204.1).[12] From 2 to 3 fuel is injected and ignited from the heat of compression. This process is also called constant pressure heat addition. During the process from 3 to 4 hot gases expand and do work on the piston. Ideally this is an isentropic expansion. As in the Otto cycle, from 4 to 1 heat is rejected by constant volume heat rejection.

Some thermodynamic relationships for the Diesel cycle include:

$R = V_1/V_2$
where:
R = Compression ratio
V = Volume

$Qin = c_p(T_3-T_2)$
$Qout = c_v(T_4-T_1)$

where:
Qin = Heat released into cylinder
c_p = Constant pressure specific heat
c_v = Constant volume specific heat
Qout = Heat rejected into atmosphere

$Wout = c_v(T_3-T_4) + (c_p - c_v)(T_3 - T_2)$
$Win = c_v(T_2-T_1)$

where:
Wout = Work output by piston
Win = Work input by piston for compression

Thermal Efficiency

$\eta_{th} = (Qin - Qout)/Qin = (Wout - Win)/Qin$
where:
η_{th} = Thermal efficiency

204.1 ACTUAL DIESEL CYCLE

Many of the same items that cause the S.I. engine to vary from the ideal Otto cycle cause the actual diesel engine to vary from the ideal cycle. Lower specific heat ratios, dissociation, blow down losses, pumping losses, the exhaust gas

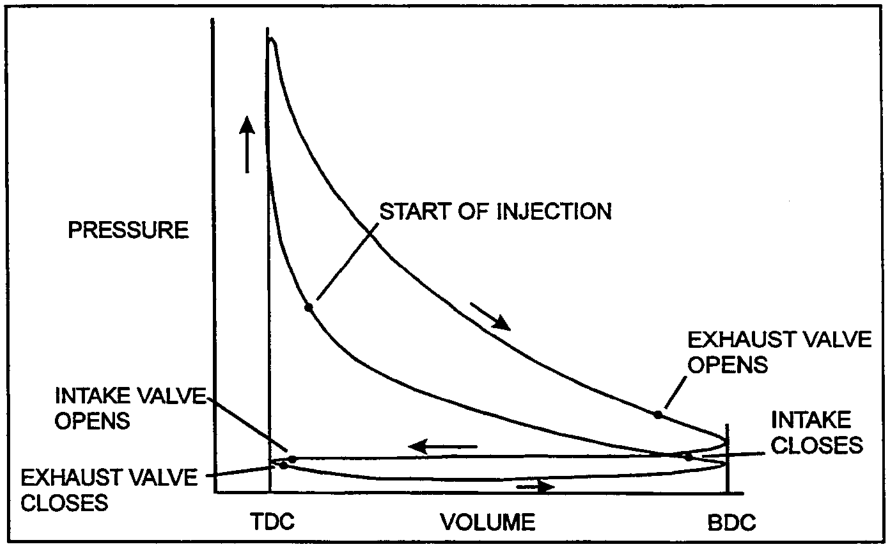

Figure 204.2 Actual P-V Diagram from C.I. Engine

effect and heat losses also apply to the C.I. engine. In addition, in the ideal diesel cycle constant pressure heat addition is assumed from 2 to 3, but in the actual cycle heat is not added at constant pressure (Fig. 204.2). Especially in high speed diesel engines the addition of heat approaches a constant volume process as indicated by the pointed peak of the P-V diagram. In some low speed engines the addition of heat approaches a constant pressure process.[13]

205 BASIC PARTS AND OPERATION OF RECIPROCATING ENGINES

Lean-Burn Engine

Rich-Burn Engine

Reciprocating internal combustion engines can be divided into two types: the spark ignition (SI) engine (the Otto cycle engine) and the compression ignition (CI) engine (the diesel engine). Engines can also be classified as lean-burn or rich-burn engines. Lean-burn engines tend to be larger and more efficient and have more than 4% oxygen in the exhaust gas while rich burn engines have under 4% oxygen, according to the definition used by California air districts. However, the definition from the Environmental Protection Agency (Reference 2, see Section 303.1), differs. All compression ignition engines are lean-burn engines. Spark ignition engines can be either lean-burn or rich-burn engines. A common myth has been that the existence of a turbocharge on a spark ignition engine would make it a lean-burn engine, but the existence or absence of a turbocharger will not determine the state of combustion. The only way to determine the combustion mode on a spark ignition engine is by direct measurement of the exhaust oxygen level. Most of the major parts of the reciprocating engine are found in the previously mentioned types of engines. The cylinder of an engine is the container in which the piston travels in a linear or "reciprocating" motion. The area above the upper part of the cylinder forms the combustion chamber. When the piston reaches the highest point of its movement (which is called Top Dead Center or TDC) there is a small area left above the piston. This area is called the "clearance volume" or "squish gap" (Fig. 203.1 and 205.1).

Top Dead Center (TDC)

Clearance Volume

The piston fits loosely within the cylinder so it can move freely. Piston rings, which are metal rings that fit around the piston, are used to minimize the escape of combustion gases past the piston. There are two types of rings: compression rings and oil scraper rings. The compression rings help prevent gases from blowing by the piston; there are usually two or three of these rings. The oil scraper ring helps keep lubricating oil from getting into the combustion chamber, where it would burn and cause the engine to smoke. The oil scraper ring is located below the compression rings. The rings have a gap in them so they can be spread apart slightly and pushed over the piston into grooves around the outside of the piston. The gap also allows for expansion from the heat of the engine. The rings do not provide perfect sealing, so some blowby of combustion gases is normal. A small amount of oil leakage also occurs, but this oil helps lubricate the upper rings.

The oil pan, crankcase, cylinder block, and cylinder head generally form the main body of the engine. The oil pan is connected to the bottom of the crankcase and it is a reservoir for the engine's oil. The crankshaft is mounted on bearings in the crankcase of the engine. The oil in the engine lubricates these bearings. The cylinder block is a metal casting of the cylinders of the engine. The cylinder block is connected to the top of the crankcase. The cylinder head is mounted to the top of the cylinder block of the engine. The cylinder head also often contains the valves and spark plugs. Figure 205.1 illustrates a simplified drawing of major parts in an engine.

A gasket called the head gasket is fitted between the cylinder head and the crankcase. The head gasket helps prevent leaks of combustion gases from irregularities between the mating surfaces of the cylinder head and cylinder block. The cylinder head and cylinder block are often different materials so they have different expansion rates, but the head gasket helps provide sealing.

200 THEORY & OPERATION

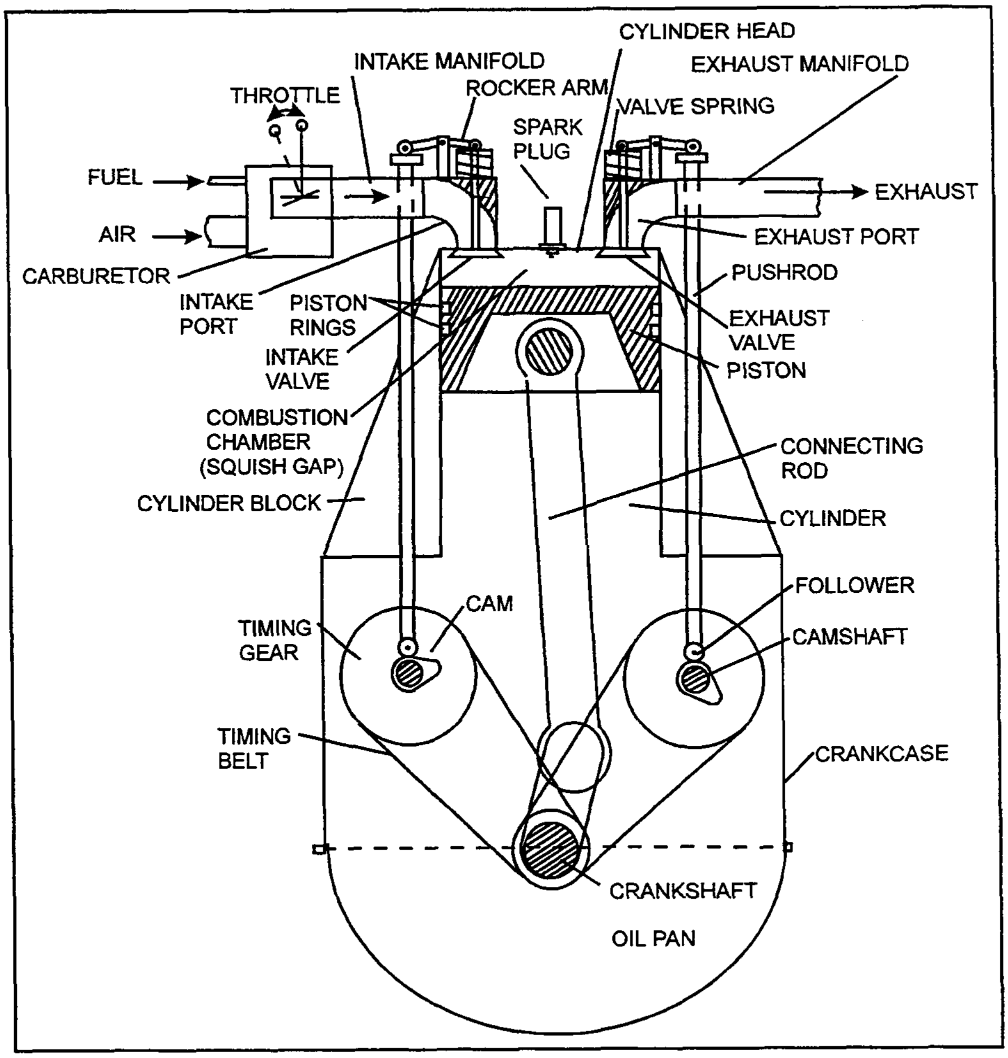

Figure 205.1 Major Engine Parts (Simplified)

If the head gasket leaks, the compression of the engine will be reduced and power will be lost. A cylinder with a leak through the head gasket will have poor combustion and it may not fire at all. If the cylinder does not fire, excessive amounts of hydrocarbons will be released into the atmosphere. The engine will also run roughly and may experience coolant loss and overheating.

A mixture of air and fuel enters the cylinder through the intake manifold. Combustion of the air/fuel mixture in the cylinder of an Otto cycle engine is initiated by a spark from a spark plug which is located at the top of the cylinder. Gases from combustion force the piston down the cylinder. The energy from the expansion of the gases is transferred to the piston and through the piston pin or wrist pin, down through the connecting rod and to the crankshaft. When the piston rises again, it forces exhaust gases out of the engine through the exhaust manifold.

The crankshaft transmits the linear reciprocating motion from the piston into rotary motion. A heavy wheel called a flywheel is connected to the crankshaft. The inertia of the flywheel turns the crankshaft so it can coast through the intake, compression, and exhaust strokes. The energy from each power stroke may vary slightly, but the flywheel provides a relatively constant rotational speed and reduces vibration. The rotary motion of the crankshaft can then be used to do work (i.e. run a generator, pump, compressor etc.).

Bottom Dead Center (BDC)

From top dead center (TDC, the top limit of the piston's travel) to bottom dead center (BDC), the bottom limit of the piston's travel) and vice-versa the crankshaft rotates 180°. In the ideal cycle the crankshaft rotates 180° for the compression cycle from 1 to 2 and for the expansion cycle from 3 to 4.

205.1 VALVE MECHANISMS

The rotational output of the crankshaft is also used to operate the intake and exhaust valves of reciprocating internal combustion engines (valves on the engine may also be called poppet valves). A separate shaft called the camshaft is connected to the crankshaft through a chain, belt or gears. These elements are called the "timing chain" or "timing belt." The timing between the camshaft and crankshaft is critical, because the valves must open and close at the correct time for proper engine operation. A change of just a few degrees from the correct setting can affect engine performance and an excessive change can cause an engine to idle roughly, lose power, increase the release of pollution emissions, and have starting difficulty.

On the camshaft are cam lobes (Fig. 205.1 and 205.2). As the cam lobe rotates with the camshaft, it contacts the follower. During the rotation of the cam, the widened portion of the cam pushes the follower. In an engine with push rod operated valves, the motion of the follower is transmitted to a push rod and then to a rocker arm. The rocker arm "rocks" in a seesaw motion, pushing the valve open each time it is actuated by the push rod.

Valve springs keep the valve tightly closed until it is opened by the motion of the rocker arm. Valve springs are very stiff and are made with high strength steel. The high stiffness of the spring prevents the valve from "chattering." It is important that the intake and the exhaust valve have good seals, so they are machined with close tolerances. Improperly sealing valves can cause an engine to idle roughly or lose compression. Sometimes a popping noise can be heard when a valve does not seat properly. Valve seat wear, valve warpage, or valve overheating can cause improper seating.

Double Over-Head Cams (DOHC)

There may be two to four valves for every cylinder. There may be one intake valve and one exhaust valve or there may be two intake valves and two exhaust valves. With two intake valves the power of the engine is increased, since more air can get into the engine and volumetric efficiency is increased. If there are four valves per cylinder, the complexity of the engine is increased. These engines may be equipped with double overhead cams (DOHC), where a separate camshaft is used to actuate a pair of valves for each cylinder (Fig. 205.3). This

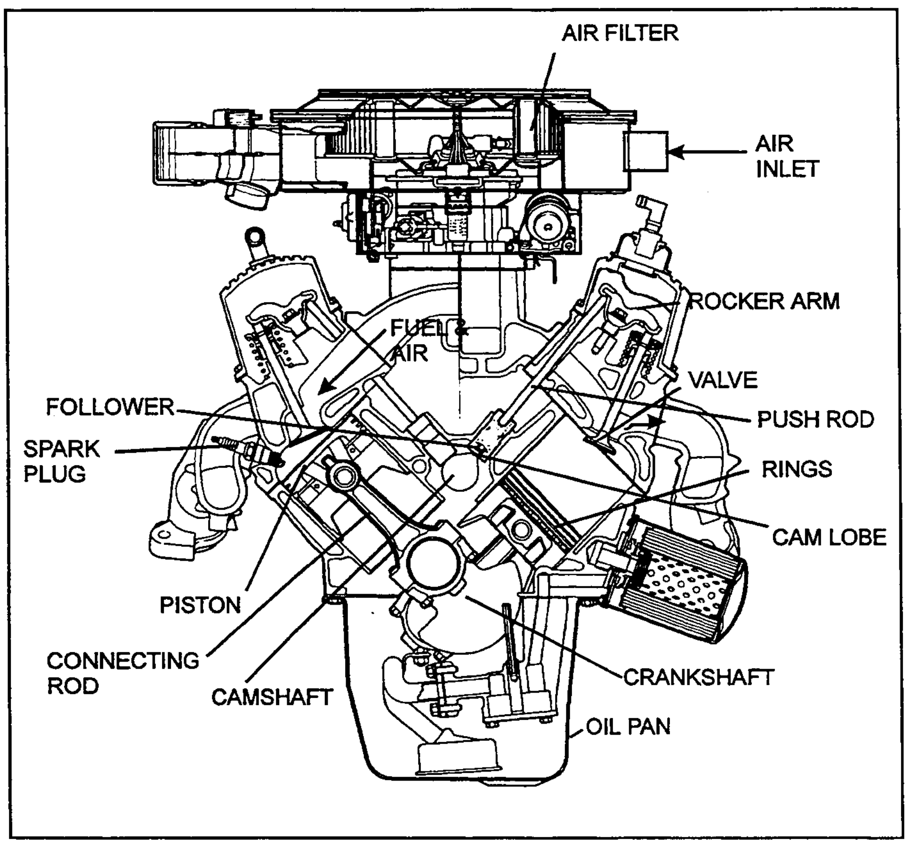

Figure 205.2 Main Parts in Actual Engine

type of valve mechanism does not use push rods, it uses lifters which are actuated by the cam lobes or it may use rocker arms. An advantage of the overhead design is that pushrods and rocker arms can be eliminated. Many automotive engines use this design.

205.2 ENGINE DESIGNS

Most stationary engines have cylinders that are either an "in-line" or a V-type design (Fig. 205.4).[14] In the in-line design, all the cylinders are aligned in a single row. Engines with four cylinders often have this design and sometimes six cylinder engines will have it too. In the V-type design there are two banks or rows of cylinders, and these banks are usually at an angle of 60 or 90 degrees. The V-type engine is essentially two in-line engines with a common crankshaft. Engines with six, eight, ten, or twelve cylinders often use this design.

Radial type reciprocating engines were often used for large and medium sized aircraft before the development of gas turbines. They have cylinders equally spaced around the crankshaft. The in-line, V, and opposed cylinder types are used for smaller aircraft. The X-type is basically two V-type engines or four in-line engines with a common crankshaft and it is also similar to the radial engine. The X-type engine is sometimes referred to as the "pancake" engine.

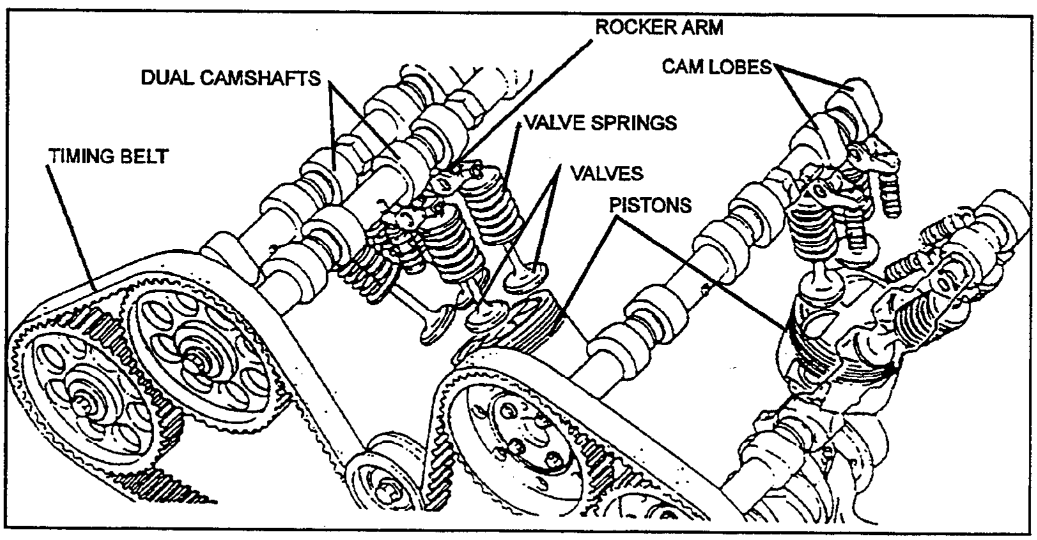

Figure 205.3 Engine with Dual Overhead Cam Design

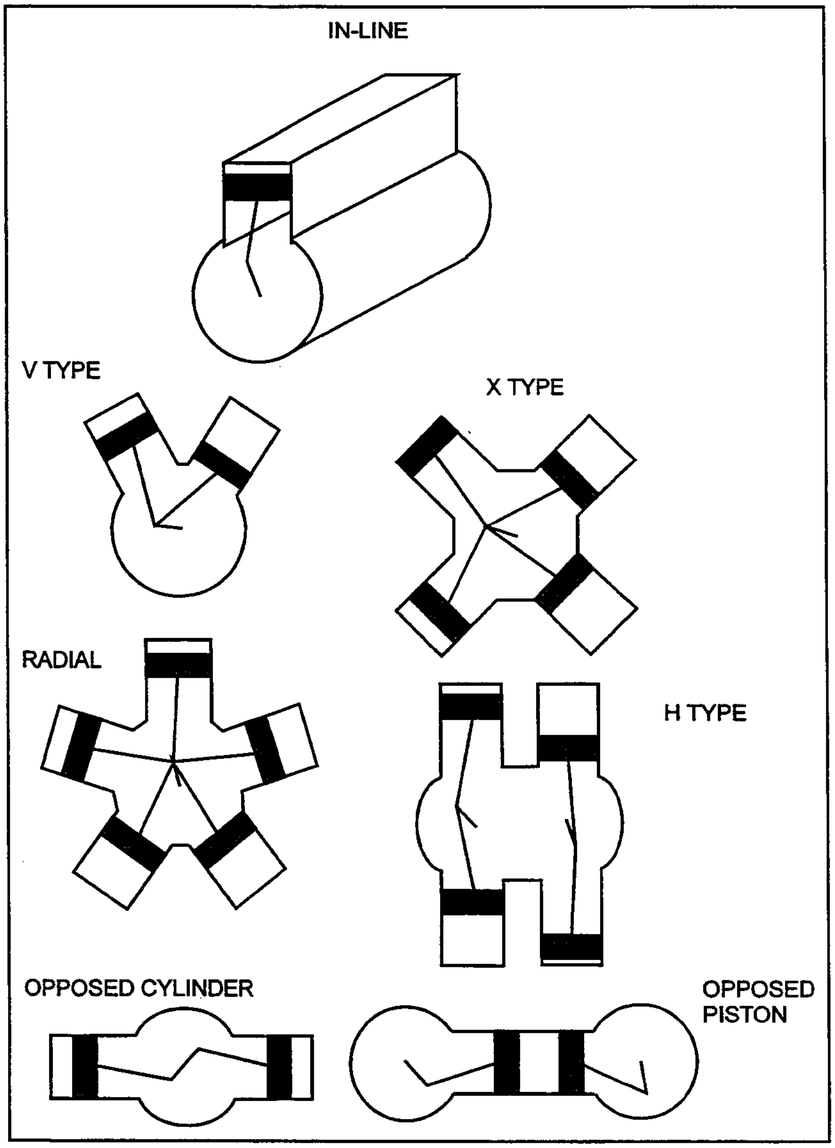

Figure 205.4 Cylinder Arrangements

The opposed cylinder engine has two or more cylinders mounted on opposite sides of the crankshaft. It is essentially two in-line engines with a common crankshaft mounted 180° apart. The opposed cylinder engine is most well known as the engine for the Volkswagen "bug" automobile. The H-type engine is two opposed cylinder engines utilizing two separate, but interconnected, crankshafts. The H and X-types of engines are rarely used but diesel engines have used this design.

205.3 DIESEL ENGINES

Many people contributed to the development of the diesel or compression ignition engine. With the work and ideas of his predecessors, Dr. Rudoph Diesel developed the compression ignition engine. This is why the engine is often called the "Diesel" engine. He was given a patent for the engine in Germany in 1892. The first compression ignition engine in the United States was installed in a St. Louis brewery in 1898.[15]

Diesel or compression ignition engines are similar to spark ignition engines, but there are differences in their design and applications. Diesel engines do not have spark plugs because they ignite the fuel by heat of compression. The energy applied to the air and fuel mixture in the cylinder by the piston moving up the cylinder causes the temperature of the air and fuel to rise. An example of the effect of the heat of compression is the heat generated by pumping a tire with a bicycle pump. When an air pump is operated the pump gets hot from the energy that the person is imparting on the air in the pump. In a diesel engine, the temperature of the mixture in the cylinder must be raised above the ignition point of the fuel during compression for the engine to run. Ignition in a diesel engine is called "spontaneous ignition" or "self ignition."

Diesel engines have a higher compression ratio, which generally ranges from 11.5:1.0 to 22.0:1 instead of 6.0:1.0 to 12.0:1.0 for the spark ignition engine. Diesel engines are more efficient than spark ignition engines because of the higher compression ratios. The efficiency of diesel engines generally ranges between 25 and 40%. The peak pressures inside the combustion chamber of compression ignition engine are much higher than the peak pressures in a spark ignition engine. Because of the high pressures attained in the diesel engine, it is built stronger and heavier than SI engines. Diesel engines are therefore more expensive, but they are more durable and generally last longer than SI engines.

The higher compression ratios of diesel engines makes them harder to start because more effort is required to overcome the high compression ratios. Cold weather increases starting difficulty, because the temperature inside the cylinder has to be increased further to ignite the fuel by the heat of compression. Some diesel engines may have glow plugs, which are resistance heaters, to assist in the starting of the engine.

Diesel engines can also run on fuel oil and even crude oil, but gasoline would make a poor diesel fuel, because at high compression ratios gasoline can autoignite and burn so quickly that knock occurs. Knock rattles engine parts and may damage them. Autoignition occurs because excessively high compression in a cylinder raises the temperature too high. The lower compression limit of gasoline engines limits their efficiency.

The temperature of the exhaust is lower from a compression ignition engine. The amount of air relative to fuel is higher, so this reduces the exhaust temperature. Since compression ignition engines are more efficient, more energy is used to perform useful work for the engine and less is lost through the exhaust. The fuel economy of the diesel engine is better than the SI engine because of the higher compression ratio, which makes the diesel engine more efficient, and because of the throttling mechanism. Gasoline engines restrict air flow to vary (or throttle) power output, which is inefficient, while diesel engines vary the fuel injected.

Diesel Knock

Diesel engines make more noise than spark ignition engines because of a condition called "diesel knock." This is due to the explosion of a small amount of fuel at the beginning of each combustion cycle as fuel is being injected into the combustion chamber. After injection of the fuel there is a short delay and a small amount of the fuel explodes, producing the noise. The rest of the fuel is burned as it is injected. Diesel knock is more noticeable after cold starts. Modifications in the design of the pistons and cylinder have been done to reduce diesel knock.

Since diesel fuel contains more energy per gallon relative to gasoline, diesel engines work well for heavy duty applications. Diesel engines can handle higher loads and they operate at slower speeds. This makes diesel engines well suited for use in construction equipment, trucks and stationary engines. However, diesel engines do not respond as well as spark ignition engines to changes in load.

The fuel injection process is one of the most important parts of the engine's operation and has a large effect on the ignition efficiency and emission characteristics. Injectors must inject fuel at very high pressures in order to overcome the high pressure from compression and to atomize the fuel. Some of the important fuel injection parameters include the injection pressure, injection timing, the geometry of the fuel spray, and the delivery rate. The amount of fuel injected controls the engine's speed and power output. The fuel and air only have a few milliseconds to mix, and good mixing is important.

A major difference between gasoline and diesel engines in fuel delivery is the way the air and fuel are mixed. In a gasoline engine fuel and air are mixed before the mixture is introduced into the combustion chamber, but in diesel engines fuel is injected directly into the combustion chamber.

Compared to modern SI engines, diesel engines often have higher emissions of NOx and in almost all cases have higher particulate matter emissions. Almost all newer SI engines have been built or modified to have low NOx emissions, but older spark ignition engines operating 10% lean of stoichiometry can easily have NOx emissions higher than many diesel engines. Diesel engines have relatively lower emissions of carbon monoxide and hydrocarbons when compared to spark ignition engines.

205.4 DUAL FUEL ENGINES

Dual fuel engines are compression ignition engines that use diesel fuel and a supplementary fuel. The supplementary fuel is usually natural gas, but propane and even methanol can be used. They operate very similarly to diesel engines and they may operate on a wide percentage of diesel fuel, ranging from 100% diesel to as little as 1%. Many older dual fuel engines obtained about 5% of their energy from diesel fuel, but newer prechamber dual fuel engines may use as little as 1%. An advantage of dual fuel engines is that they can attain higher efficiencies than spark ignition engines (CI engines are more efficient than SI engines), but they have lower emissions than diesel engines.

205.5 TWO STROKE CYCLES

Piston Stroke

Reciprocating engines may operate in a two or four stroke cycle, where a stroke is one complete movement of the piston from one end of the cylinder to the other. In a two stroke cycle, a complete power cycle is completed for every revolution of the crankshaft. Therefore, one complete motion of the piston from one end of the cylinder to the other and back again is a complete power cycle. Power from the combustion of air and fuel in the cylinder is produced once every power cycle.

Figure 205.5 illustrates the two stroke engine cycle with a reed valve.[16] As the piston moves to the top of its travel (Top Dead Center) the increasing volume below the piston causes the reed valve to open and air enters the crankcase of the

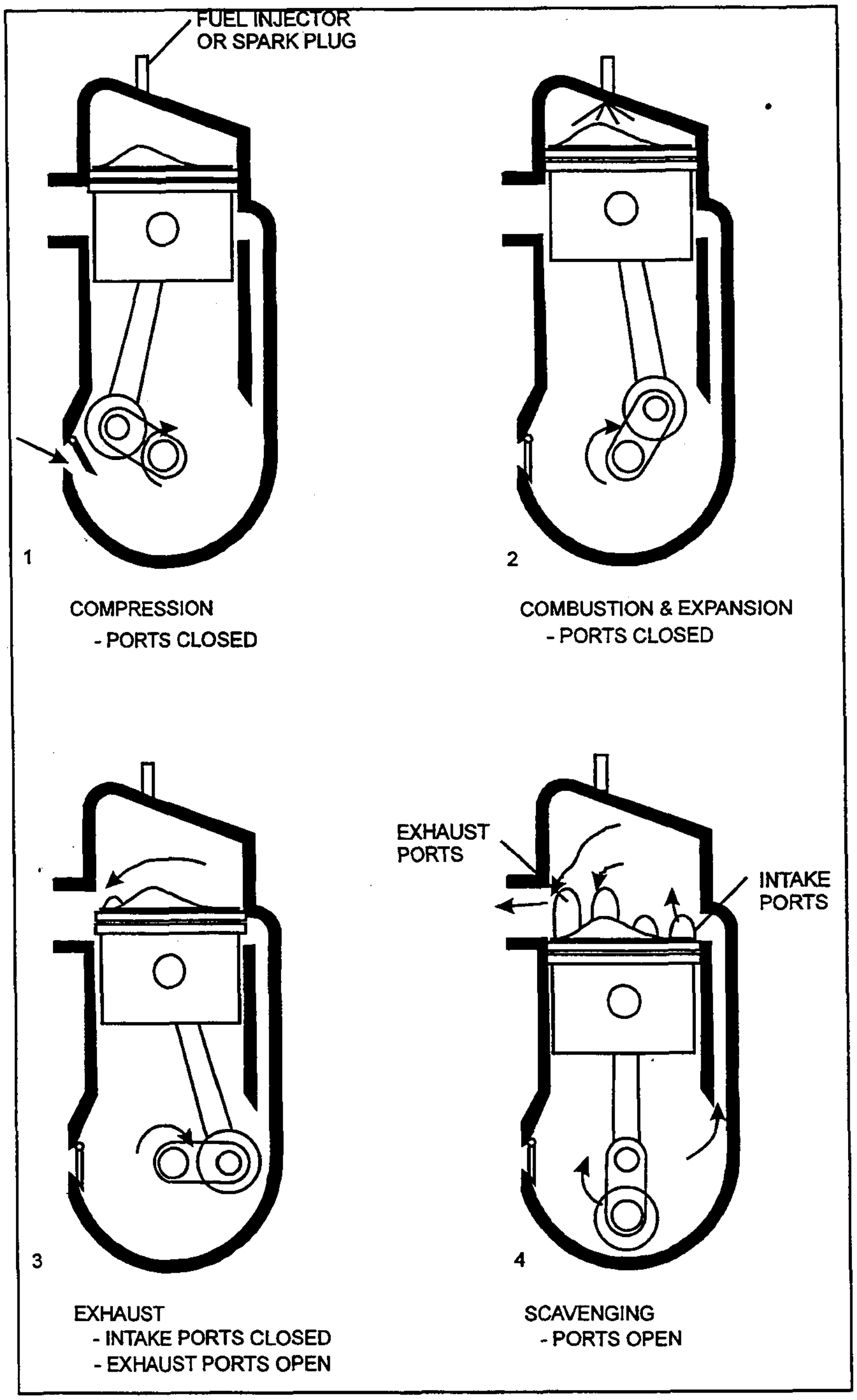

Figure 205.5 Two Stroke Cycle (Reed Valve)

engine. This air will be used later during the cycle for intake and scavenging. At the same time, the air or air/fuel mixture above the cylinder in the combustion chamber is compressed, and then ignition occurs. Power is delivered to the piston by the expansion of gases from combustion and as the piston moves down the cylinder, exhaust ports are exposed (in other two stroke design, exhaust valves may open). Exhaust gases then begin to exit the cylinder, since the pressure inside the cylinder is higher than outside the cylinder, but the pressure in the cylinder rapidly drops toward atmospheric pressure. At the same time, the reed valve closes once the piston begins its descent and the air in the crankcase is compressed by the piston's motion. When the intake ports are opened, fresh air from the crankcase helps push out any remaining exhaust gases. This cleansing of the cylinder is called scavenging.

Scavenging

In other two stroke designs a low pressure blower may provide scavenging and valves may be used instead of ports. The air from the crankcase that provided scavenging is also used on the intake stroke and air flows into the cylinder through the intake ports during the pistons' downward motion when the intake ports are open. Small engines such as those for chain saws, some motorcycles, model airplanes, and outboard motors often are two cycle engines. Small engines may use the reed valve design.

The operation of removing exhaust gases from the cylinder and filling it with fresh air is called "scavenging." In commercial or large two stroke engines the air or air and fuel mixture can be supplied to the cylinder by a scavenging pump. This helps force exhaust gases out of the cylinder. The intake air may also be pressurized by a turbocharger or supercharger. Most industrial two stroke engines are Diesel engines and are turbocharged or supercharged. Spark ignition engines can also operate as two stroke engines.

During scavenging in engines with valves, both the inlet and exhaust valves are open at the same time. The scavenging period also allows engine parts to cool. This helps prevent the air/fuel mixture from igniting too early.

Unfortunately, scavenging is not perfect. Some air could pass through the engine and out the exhaust ports. This is called short circuiting. Some air will mix with exhaust gases and a portion of this mixture will be pushed out of the engine by the remaining incoming air. The severity of this problem is dependent on the design of the ports, and the shape of the top of the piston. A portion of the fuel charge may be wasted during scavenging, especially in carbureted gasoline engines because there is an air/fuel mixture for the intake stroke. This leads to a waste of fuel and hydrocarbon emissions.

There are a number of different ways an engine can be designed to operate in a two stroke cycle (Fig. 205.6).[17] All of these engines have ports, but "E" also has valves. Engines "A" and "B" have ports at the bottom of the cylinder opened and closed by the piston, with one set of ports for intake of air or air and fuel and the other set for exhaust. In engines "C" and "D" inlet ports are opened and closed by one cylinder and exhaust ports are opened and closed by another cylinder. Engine "E" has valves at the cylinder head end (the top) of the engine. Engine "F" has piston controlled ports similar to all engines except engine "E." Engines with ports on one end of the cylinder as in "A" and "B" are often called "loop-scavenged."[18] Engines with ports on both ends of the cylinder are often called "through-scavenged." The hump on the piston in engine "A" helps force air to turn and mix with exhaust gases for scavenging. Without the hump, air

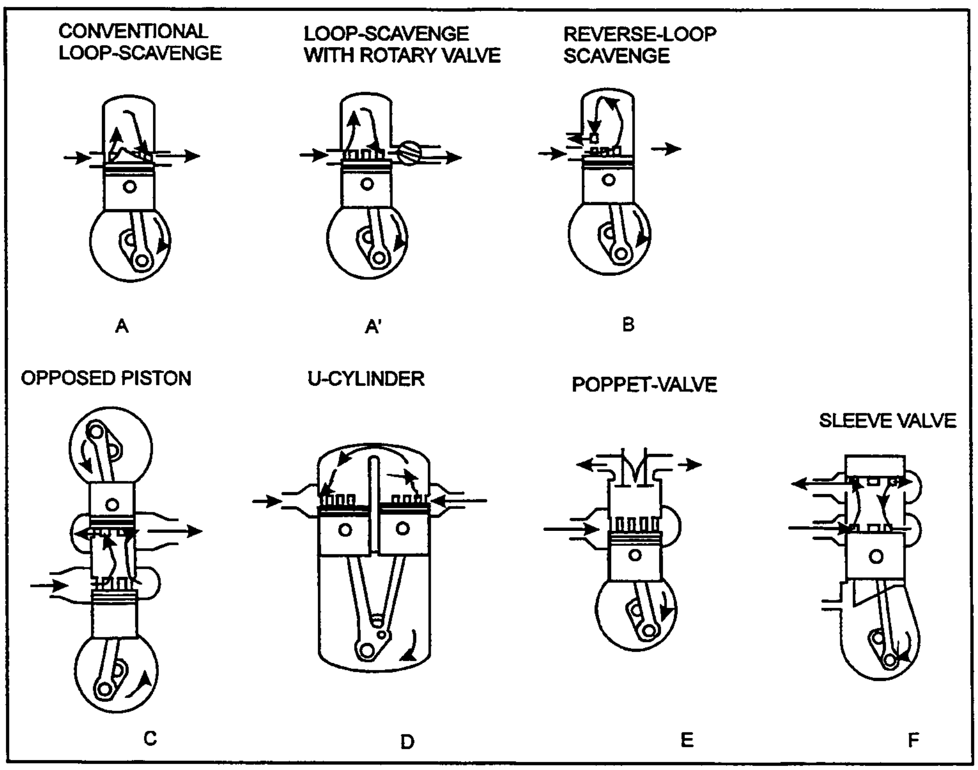

Figure 205.6 Two Stroke Cylinders

would tend to short circuit out the exhaust port exit without mixing with the exhaust.

Two stroke engines have a higher horsepower to weight ratio than four stroke engines, but two stroke engines tend to have higher emissions. Two stroke diesel engines have lower amounts of emissions (except for NOx) than two stroke spark ignition engines. The fuel economy of two stroke engines is generally less than four stroke engines, since some of the fuel charge may be lost during scavenging. Scavenging is not perfect, since some of the air used to remove exhaust from the cylinder can short circuit through exhaust ports, and exhaust gases may remain in the cylinder after the process. The use of ports in the two cycle engine simplifies the design, but the combustion in four cycle engines is easier to control.

205.6 FOUR STROKE ENGINES

A four stroke engine completes one power cycle for every two revolutions of the crankshaft. Therefore, there is one power stroke for every two revolutions of the crankshaft. The four strokes include: intake, compression, ignition and power, and exhaust (Fig. 205.7). During the intake stroke a charge of air or air/fuel is drawn or blown into the cylinder as the piston moves down the cylinder. A diesel engine will have an air charge, but an Otto cycle engine will have an air and fuel mixture for the charge. Whether or not the charge is drawn or blown into the cylinder depends on how the charge is put into the engine (i.e. natural aspiration, turbo charging etc.).

During the compression stroke the piston moves up the cylinder, reducing the volume of the space above it. The air or air and fuel mixture is therefore compressed by the piston. The compression ratio for an Otto cycle engine is generally 6:1 to 12:1, and for a diesel engine it is generally 11:1 to 22:1.

The ignition and power stroke begins once the piston comes near top dead center. Ignition occurs by a spark in an Otto cycle engine or by the heat of compression in a diesel engine. The rapid expansion of exhaust gases pushes the piston down the cylinder. A pressure as high as 600 psi or more may be created in the cylinder during the power stroke in a spark ignition engine. When the piston begins its upward travel again the exhaust stroke begins. Exhaust valves open and the motion of the piston up the cylinder helps push exhaust gases out through the exhaust valve opening. This prepares the cylinder for the next four stroke cycle.

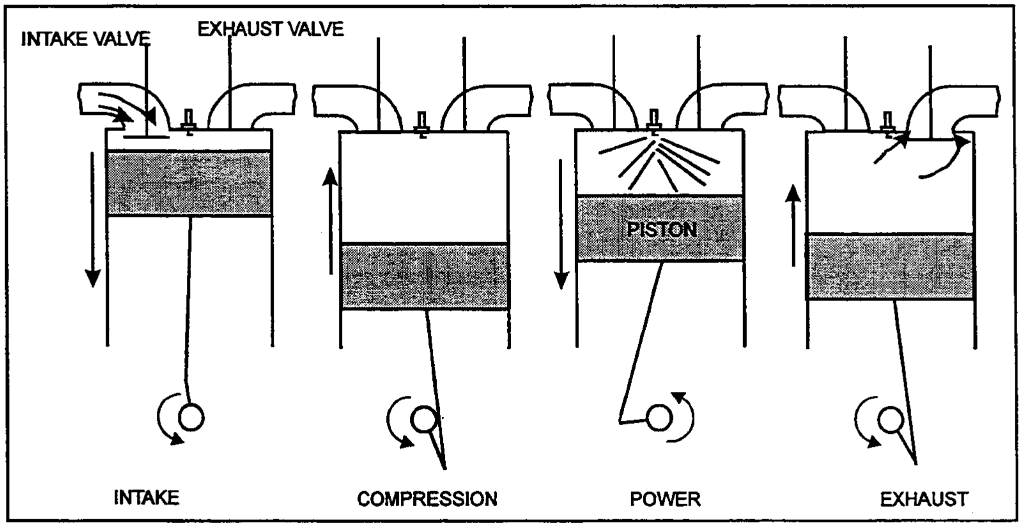

Figure 205.7 Four Stroke Cycle

Engines with more than one cylinder will go through the four stroke cycle at different times. This staggers the power strokes so that the engines will operate smoothly. The order which the power strokes occur is called the firing order.

205.7 CHARGING

A "charge" is the air or air/fuel mixture that is put into the cylinder before combustion. The main methods of charging for reciprocating engines include: natural aspiration, turbocharging, supercharging and blower-scavenging.

205.7.1 Natural Aspiration

An engine that is naturally aspirated uses the decreased pressure formed in the cylinder when the piston moves down toward bottom dead center to draw in fresh air. Two or four stroke engines may be naturally aspirated. For four stroke engines the volume of air drawn into the cylinder by natural aspiration is only 50 to 75% of the displaced volume, so natural aspiration is not a very efficient charging method.[19] For two stroke engines blowers are a more efficient method of charging the cylinder. An engine that is naturally aspirated also indicates that it is not supercharged or turbocharged.

205.7.2 Supercharging and Turbocharging

Superchargers and turbochargers are mechanisms used to increase the density of the air entering the engine for combustion. This increases the mass flow rate and pressure of the air entering the engine. The power output of an engine with supercharging or turbocharging is increased, since with more air entering the engine the amount of fuel entering the engine can be increased to keep the same air/fuel ratio.

Supercharger

In a supercharger a compressor is used to put more air in the engine. The compressor is usually driven by a belt from the crankshaft of the engine. Superchargers are used when increased air density (boost) is desired at all engine speeds. They are often used in engines for racing applications. Supercharging also improves the mixing of air and fuel and increases the turbulence in the combustion chamber. Turbulence is one of the three T's of combustion; the other two are time and temperature. Increasing any or all of the three T's of combustion generally improves combustion.

Turbocharger

A turbocharger is similar to a supercharger, but the compressor wheel is directly driven by a turbine wheel (Fig. 205.8, 205.9). Exhaust gases from the engine pass through the vanes of turbine. As the exhaust passes through the turbine, the pressure of the hot gases acts on the turbine blades, causing the turbine to rotate. A shaft from the turbine is connected to the compressor. At low speeds the boost from the turbocharger is at a minimum, but at high speeds it is at a maximum. Furthermore, the boost is relatively low at part throttle and high at wide open throttle. Both two and four cycle engines can be turbocharged or supercharged.

Turbochargers are generally designed to increase the output power approximately 1.5 times.[20] Some engines may be made with stronger construction so they can operate with turbochargers that raise the engine charging capacity to two to three time its naturally aspirated value. The power increase from turbocharging allows a smaller engine to be used for a given application. Turbocharging also makes an engine more efficient, since energy that would be lost in the exhaust is used to drive the turbine of the turbocharger.

Superchargers and turbochargers were initially designed to operate for aircraft engines, since the air in the atmosphere gets less dense at high altitudes. The thinner air would reduce the performance of aircraft engines, but with a supercharger or turbocharger the increased air entering the engine would keep

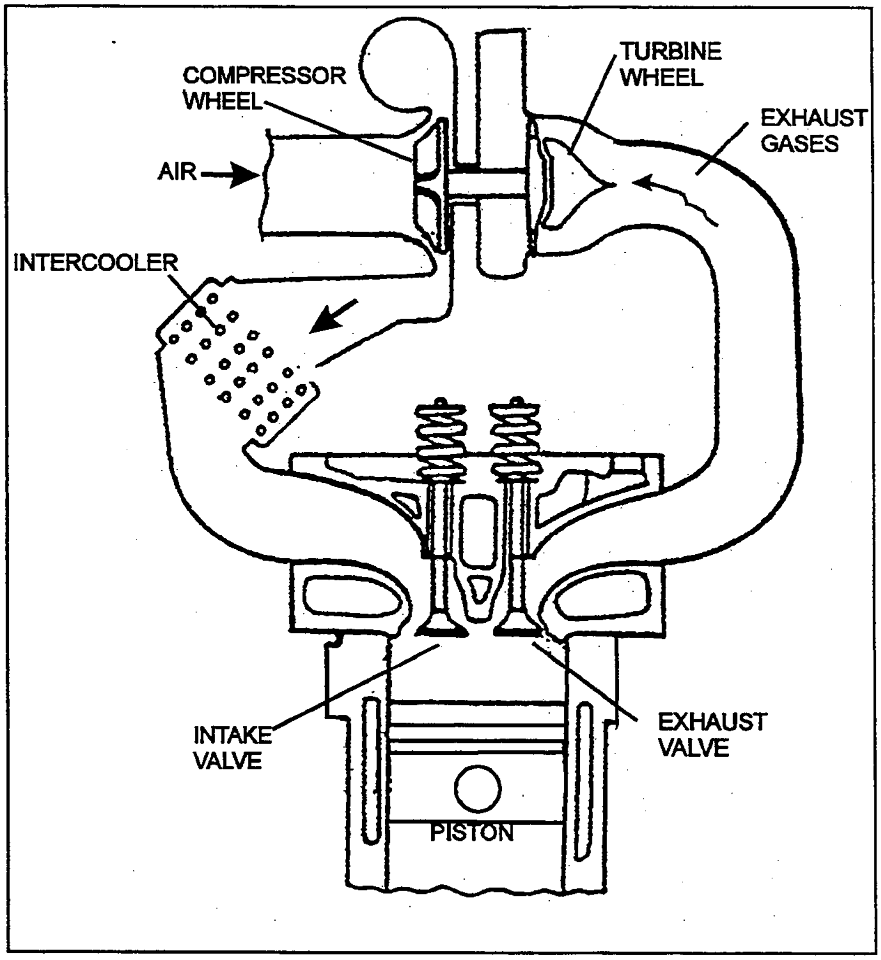

Figure 205.8 Turbocharger

the engine operating at higher altitudes. Today, most stationary diesel engines use turbochargers.

The air entering the engine is heated from compression when it passes through the compressor wheel. The increased temperature can be beneficial when liquid fuels are used because vaporization of the fuel is improved. On the other hand, a warmer charge will have a lower density and will work against the increase in density from the supercharger or turbocharger.

Intercoolers Aftercoolers

Intercoolers and aftercoolers are heat exchangers, where heat is allowed to flow from the intake air to the cooling media in the heat exchanger. It is possible to design an engine with turbochargers using more than one compression stage and

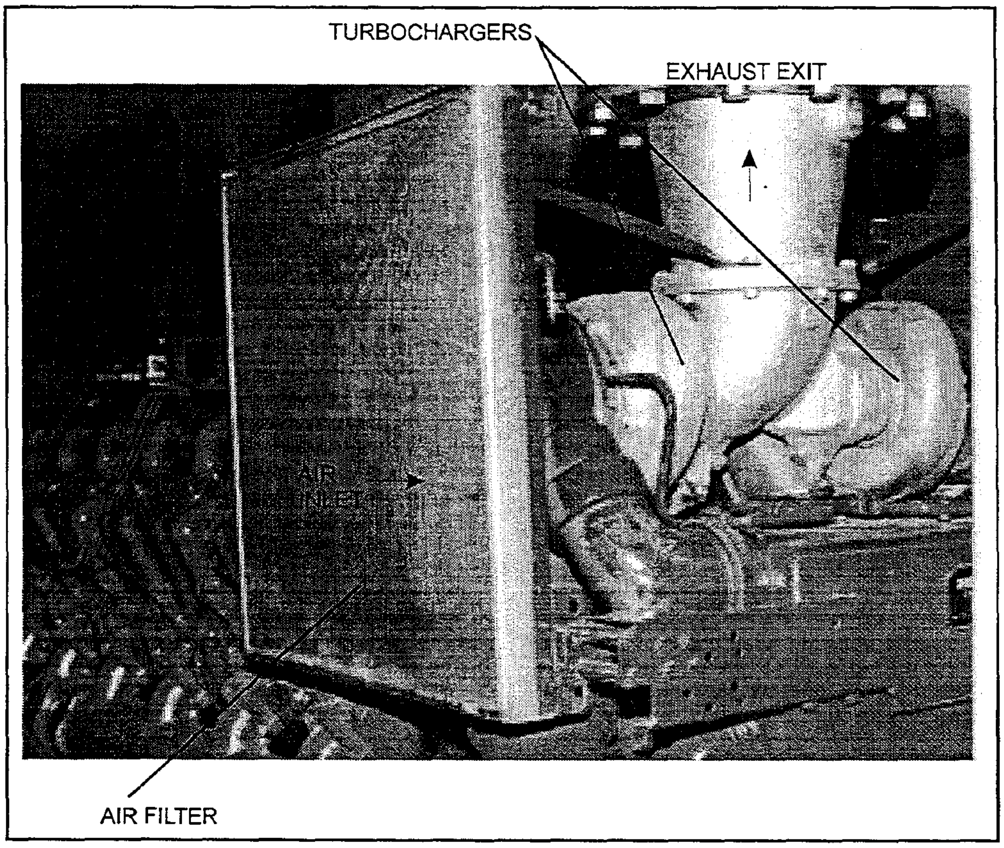

Figure 205.9 External View of Turbocharger

using intercoolers between compression stages, but aftercoolers are used after a single compression.

Intercoolers or aftercoolers can improve the performance of a supercharger or turbocharger. Intercoolers or aftercoolers cool the air entering an engine and therefore increase its density. When the air out of the turbocharger or supercharger is cooled, the mass of the air entering the combustion chamber is increased so the power output is increased. The denser, cooler charge also helps reduce emissions of NOx and may reduce particulate.

205.7.3 Blower-Scavenging

Low pressure blowers or scavenging pumps are often used to charge two stroke engines. The blowers provide a large volume flow rate of air, so they also act to scavenge the cylinder of exhaust gases. In some two stroke engines, depending on the design of the intake and exhaust, turbochargers or superchargers may be

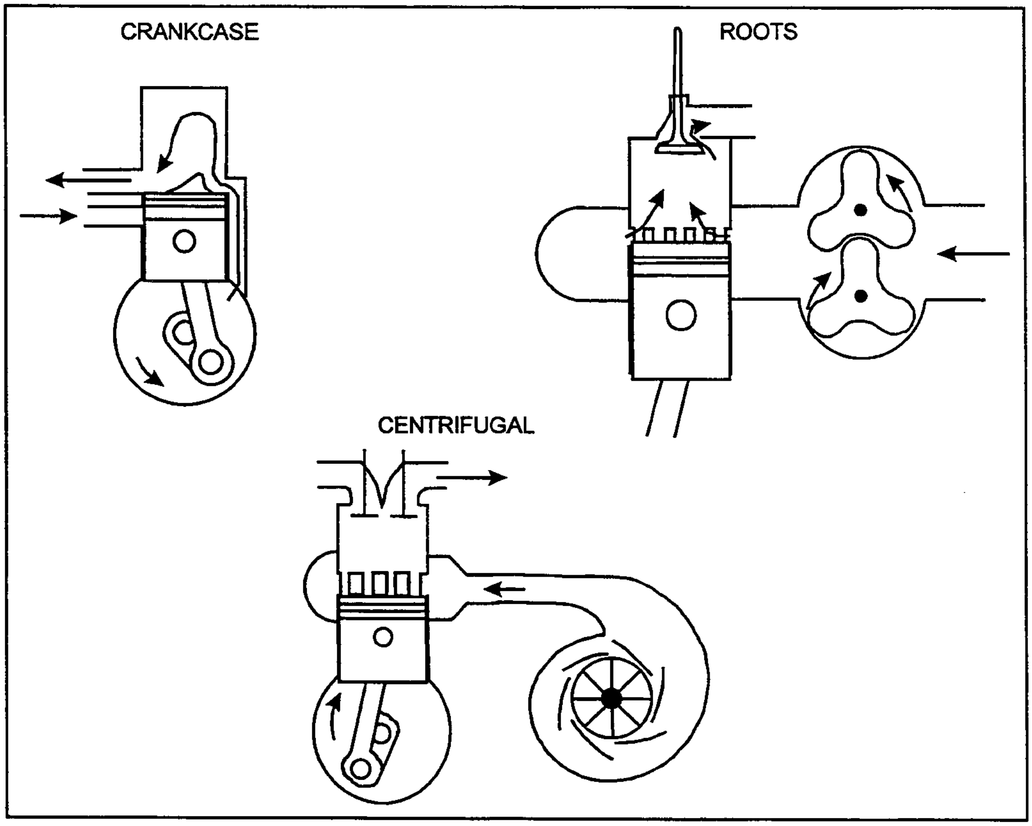

Figure 205.10 Scavenging Pumps

used for scavenging instead of just compressing the intake air or air/fuel mixture. Blower scavenging increases the pressure of the charge a small amount, but it does not increase the efficiency nearly as much as supercharging or turbocharging.[21] Figure 205.10 illustrates some common types of scavenging pumps.

205.8 FUEL DELIVERY

Fuel may be delivered to a reciprocating engine by a carburetor or fuel injection. Only spark ignition engines use carburetors and they have been used extensively for gasoline fueled engines. All of today's diesel and gasoline fueled automobile engines use fuel injection; many of today's stationary spark ignition engines use carburetors. SI engines fired with gaseous fuels use carburetors or fuel mixers.

205.8.1 Carburetors

A carburetor is a device which uses hydraulic, mechanical and/or electrical, devices for metering and mixing of fuel with air. Carburetors can be used on liquid or gaseous fuels, but this section primarily applies to carburetors for liquid fuels. Carburetors for gaseous fuels are often called fuel mixers. Fuel mixers are much simpler than liquid fuel carburetors because they have few moving parts. One vendor has a fuel mixer with one moving part and generally all other fuel mixer designs have no moving parts.

Fuel mixers

A carburetor is normally bolted to the top of the intake manifold and an air cleaner or filter is usually situated upstream of the carburetor to clean incoming air.

The main functions of a carburetor include: mixing fuel and air, atomizing liquid fuel, metering the correct amount of fuel into the air stream, controlling the amount of air entering the engine, regulating vacuum operated devices (i.e. distributor vacuum advance), and controlling engine speed and power.

Examination of a carburetor is simplified by looking at the systems operating within it. Figure 205.11 shows the main parts of a simple float type carburetor. There are seven basic carburetor systems in a carburetor and these include:[22]

1. Float system - maintains supply of fuel in carburetor bowl,
2. Idle system - provides a small amount of fuel for low speed operation,
3. Off-idle system - provides correct air/fuel mixture slightly above idle speeds,
4. Acceleration system - squirts fuel into air horn when throttle valve opens and engine speed increases,
5. High speed system - supplies lean air/fuel mixture at moderate speeds,
6. Full power system - enriches fuel mixture slightly when engine power demands are high, and
7. Choke system - provides extremely rich air/fuel mixture for cold engine starting.

Float System

Fuel enters the float chamber from the fuel tank. The amount of fuel in the chamber (or float bowl) is controlled by the fuel supply valve and the float. Fuel

Float Chamber

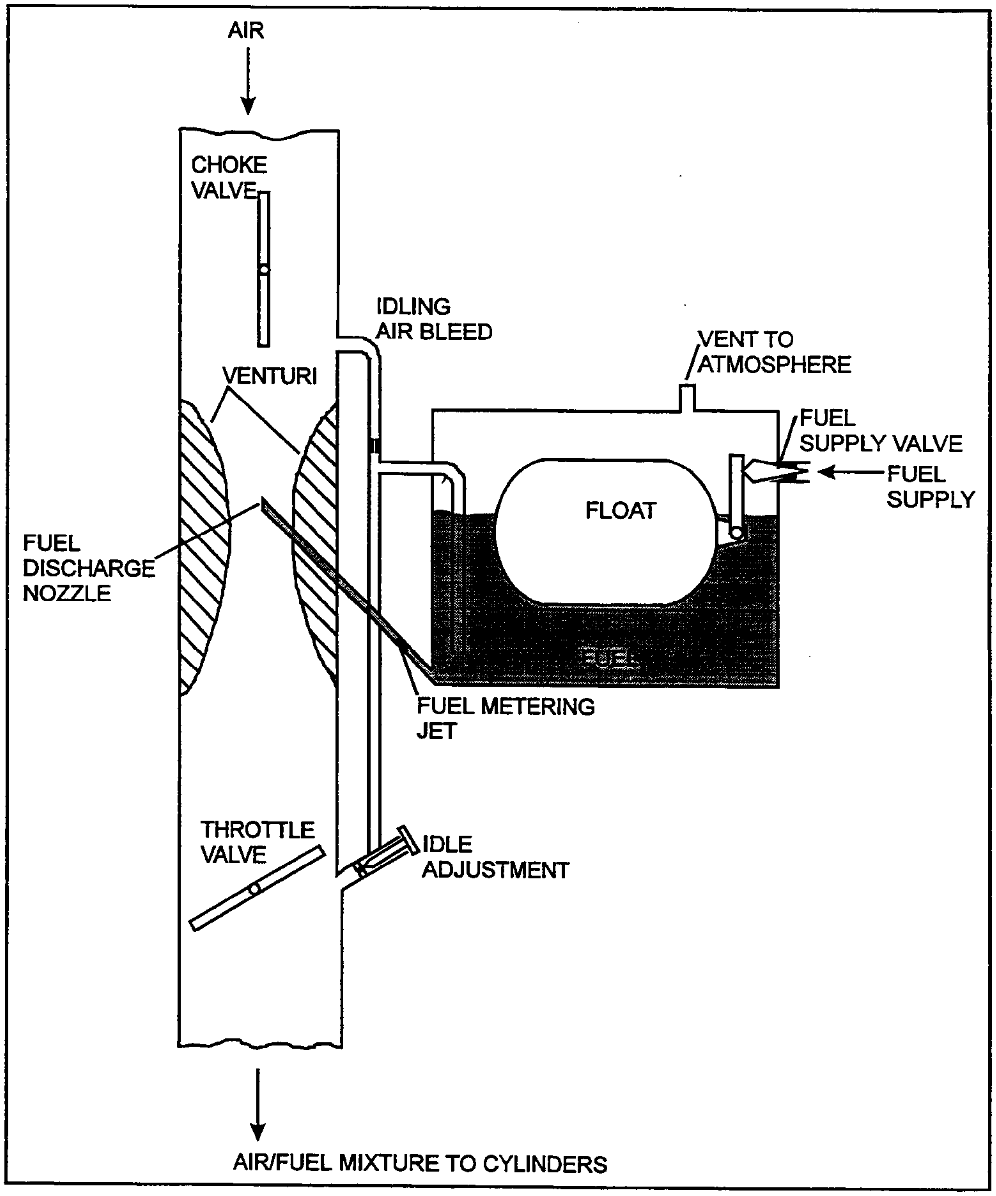

Figure 205.11 Main Parts of Float Type Carburetor

is drawn out of the float bowl rapidly, causing the float to drop with the level of the fuel in the float bowl. When the float falls below a designated level the supply valve opens causing fuel, which is under pressure from the fuel pump, to flow into the float chamber. Once the float rises, the supply valve will seat again and shut off the supply of fuel. The float chamber is vented to the atmosphere, to prevent a vacuum from forming in the float bowl or to prevent the float bowl from getting pressurized.

Idle System

At very low engine speeds or at idle, the idle system provides the correct air/fuel ratio for the engine. At idle the throttle valve is nearly closed, so there will not be a large enough air flow through the carburetor throat to create a pressure differential for the fuel to flow. When air rushes through the venturi in the carburetor throat, a pressure differential is created which makes fuel flow out the main jet.

The idle system has a fuel passage, an idle air bleed, idle air restriction and an idle mixture adjustment screw at the idle port. Beyond the idle adjustment screw, fuel and air are discharged into the air horn. Intake manifold vacuum causes air to flow in from the air bleed and fuel to flow from the float bowl. Air and fuel mix, pass by the idle adjustment screw and flow into the air horn, providing the engine with fuel and air at idle.

Off-Idle System

The off-idle system or idle transfer passage consists of holes or a slot in the air horn just above the throttle valve. It provides extra fuel during the transition from idle to higher speeds. When the throttle valve is closed the off-idle opening or openings act as additional air bleeds for the idle system. When the throttle valve swings open, the off-idle openings are exposed to intake manifold vacuum. At this point more fuel is supplied.

Acceleration Pump System

The acceleration pump system provides extra fuel like the off-idle system when the engine moves from idle to high speed. When an engine is accelerated and the throttle valve swings open, the air flow increases suddenly, and since the fuel is heavier than the air, it cannot respond as rapidly. There are different accelerator pump systems and some of these include the piston accelerator pump, the diaphragm accelerator pump, the vacuum-operated accelerator pump, and the temperature compensated accelerator pump.

High Speed System

An adequate air/fuel mixture is delivered by the high speed or main carburetor system at normal operating speeds (i.e. 2000 to 3000 rpm for an SI engine).[23] The high speed system begins to operate when the airflow through the venturi in the carburetor throat gets high enough to create a vacuum to draw fuel out of the main discharge passage. It also operates during choke, acceleration and full power, but it does not operate during deceleration or idle.

When air passes through the venturi in the carburetor throat its velocity increases, and its pressure decreases from the reduction in cross-sectional area, in accordance with the Bernoulli equation. The float bowl is vented to the atmosphere and is at atmospheric pressure, so the reduced pressure at the venturi throat causes a pressure difference. Since the end of the fuel discharge passage is in the venturi throat, fuel will flow from the float chamber out through the fuel jet and discharge passage and into the air stream. The velocity of the air is much higher than the velocity of the fuel, so the air atomizes the fuel when the two mix. As the rate of air flow through the venturi increases, the pressure differential increases and more fuel is discharged, keeping the air to fuel ratio constant. Fuel no longer flows from the idle port because the vacuum in the venturi is higher than near the idle port.

Full Power System

The full power system (also called the power enrichment or economizer circuit) supplies extra fuel for maximum power. This system is able to change the air/fuel ratio from lean to rich to meet engine demands. There are two main types of full power system, including the power valve and metering rod system. The power valve system is usually operated by vacuum, but the rod type may be operated by vacuum, mechanically, or electrically.

Choke System

The choke system is needed to provide an extra rich mixture for cold starting of an engine. During cold starts the choke valve, a butterfly valve situated before the venturi, is closed. The downward motion of the piston creates a strong vacuum in the area around the fuel discharge nozzle. This vacuum forms a pressure differential between the float chamber and discharge passage causing relatively large amounts of fuel to flow out through it.

Carburetor Use

Carburetors have been used since the development of early reciprocating engines and today's carburetors are somewhat complicated in order to meet emission requirements and their limitations. It may be difficult to run an engine with a carburetor over a wide range of operating conditions, especially if it has a simpler older type of design. For example, running the engine at the best fuel economy requires that the engine run at air/fuel ratios leaner than stoichiometric with all the fuel being consumed. In order to run the engine at maximum power, the carburetor must run richer than stoichiometric, with all the oxygen in the air entering the engine being consumed.

Changes in environmental conditions also cause problems with some carburetors. An engine running at high elevations or at high temperatures needs different carburetion than an engine at sea level or cold temperatures. Because of these problems, modern SI engines using liquid fuels usually use fuel injection rather than carburetion.

205.8.2 Fuel Injection

Fuel injection is a much more precise method of fuel delivery; it is used in all compression ignition engines, and most stationary engines and modern vehicle spark ignition engines. Fuel injection puts the correct amount of fuel in the engine at the correct time so that engine performance and fuel economy can be maximized and emissions can be reduced. With improved mixture control the thermal efficiency (fuel economy) of the engine is increased. With fuel injection the volumetric efficiency is increased, so the power output and torque of an engine increase. In a carburetor the volumetric efficiency is decreased from energy losses from the venturi. Also, lower gas velocities are required in the intake manifold since the fuel droplets are smaller. Emissions are lowered because during deceleration the fuel flow can be cut off. No choke is required since the computer that controls the fuel injection can sense when the engine is cold. Short circuiting of fuel in four stroke turbocharged and supercharged engines and all two stroke engines can be eliminated. Fuel can be nearly perfectly distributed to each cylinder, unlike a carbureted system. A fuel injected engine can run smoother at idle and a leaner mixture can be used at idle, because of improved fuel distribution and fuel atomization at low speeds.

Main Parts of the System

There are four main parts to modern electronic fuel injection systems, including: the fuel delivery system, air induction system, sensor system, and computer control system (Fig. 205.12)[24].

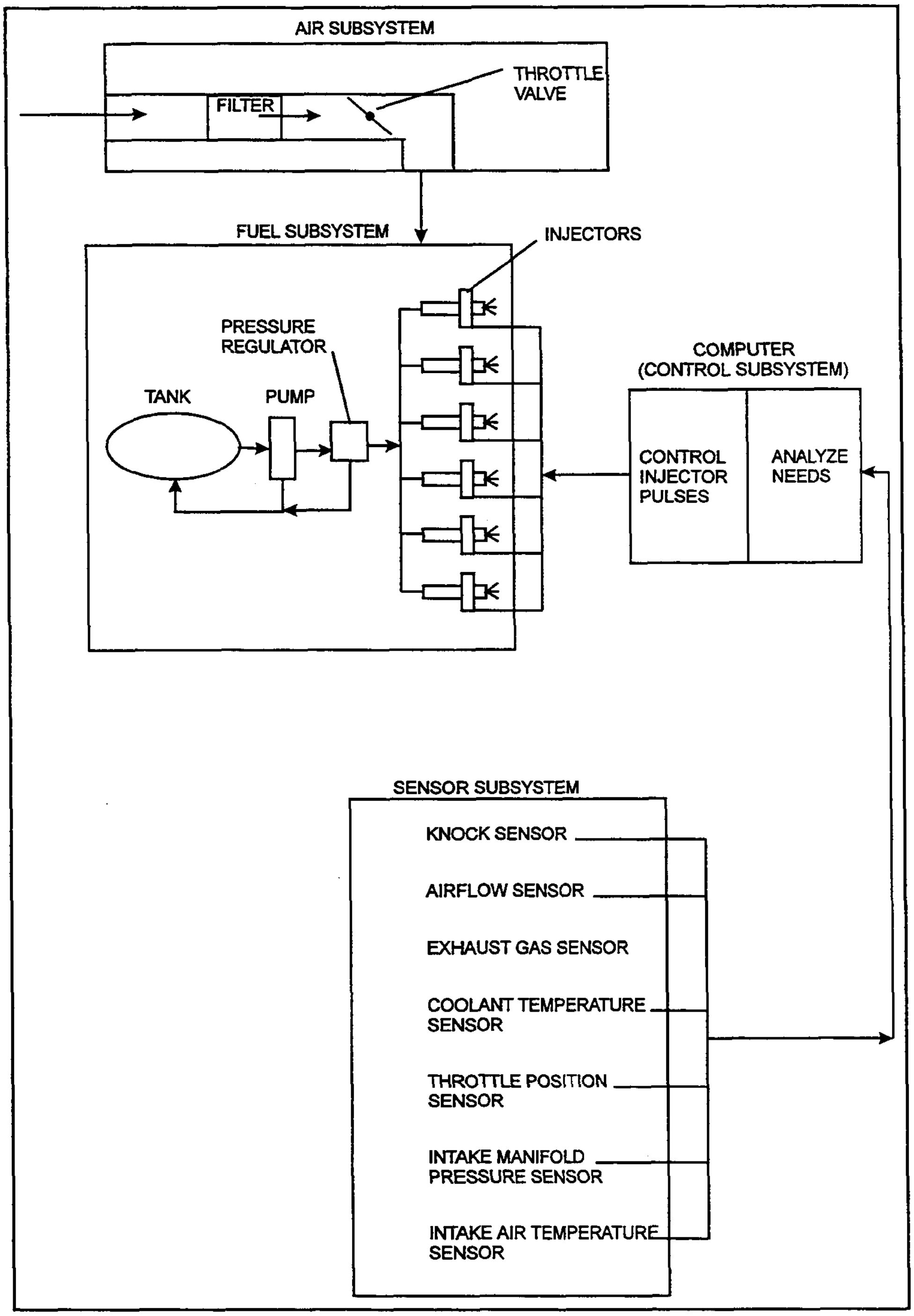

Figure 205.12 Fuel Injection Subsystems

Fuel Delivery System

The function of the fuel delivery system is to clean and meter the right amount of fuel for different driving conditions. The main parts of the system include an electric fuel pump, fuel injectors, fuel rail, pressure regulator, fuel filter and fuel lines.

The fuel pump forces fuel from the gas tank to the pressure regulator. The pressure regulator maintains a constant pressure at all the injectors. Fuel injectors act as electrically operated fuel valves. The pressure regulator is connected to the intake manifold vacuum to allow the pressure regulator to change fuel pressure when the load on the engine changes. Fuel flows through lines and sprays out the injectors when they are energized by the computer. When the injectors are deenergized by the computer, the injectors must close rapidly and not leak any fuel. Extra fuel that was not sprayed out the injectors leaves the pressure regulator and goes back into the fuel tank.

Air Induction System

An electronic fuel injection (EFI) air induction system cleans and supplies air to all the engine's cylinders. The parts common to most systems include an air filter, throttle valve, intake manifold and air ducts. The air filter cleans the air and the throttle valve controls the airflow into the engine.

Sensor System

The EFI sensor system keeps track of the engines operating conditions and sends this information to the computer. Some of the sensors in this system include the air inlet temperature sensor, engine coolant temperature sensor, throttle position sensor, intake manifold pressure sensor, and oxygen sensor. The sensor system allows the fuel injection system to check and correct itself to maintain efficient operation.

The air inlet temperature sensor measures the temperature of the air entering the engine. This sensor adjusts for changes in the inlet air temperature to maintain the proper air/fuel ratio, since colder air is denser and requires more fuel and warmer air is less dense and requires less fuel.

Depending on the design, the engine coolant temperature sensor may provide a higher current to the computer so a richer mixture can be provided, especially for cold starts. As the engine warms the sensor would reduce the current, providing a signal to the computer to lean the mixture.

The throttle position sensor behaves as a multiple position switch or variable resister. As the throttle position changes the sensor may change the current to signal the throttle position change to the computer.

The manifold pressure sensor senses the vacuum in the intake manifold. The amount of vacuum in the intake indicates the load on the engine. At higher loads there will be high manifold pressure (lower intake vacuum) and the engine will need a richer fuel mixture, but at lower loads the manifold pressure will be lower (higher intake vacuum) and a leaner mixture can be supplied. By varying current or resistance, the manifold pressure sensor provides manifold pressure information to the computer so the correct air/fuel ratio is maintained at different loads.

One of the most important sensors in the fuel injection system is the oxygen sensor or exhaust gas sensor. The oxygen sensor measures the oxygen content in the exhaust gases. This tells the computer whether the engine is running too rich or lean. Therefore, this sensor helps control pollutant emissions and fuel economy.

Computer Control System

The computer control system (electronic control unit or ECU) handles all the information input into it from the sensor system and controls the operation of the electronic fuel injection system and other systems. It is the brain of the fuel injection system. There are many inputs to the computer, such as engine rpm and all the sensors. The computer uses the input information to control outputs to run the fuel injectors, fuel pump, and other equipment.

Types of Fuel Injection Systems

Fuel injection can be categorized as direct injection and indirect injection. In direct injection fuel is sprayed directly into the combustion chamber or cylinder. All diesel engines use direct injection. In an indirect system fuel is sprayed in the intake manifold upstream from the cylinder. This allows fuel and air to mix before they enter the cylinder. Gasoline engines use indirect injection.

The following are other characteristics that are used to classify fuel injectors:[25]

Single Point - One fuel injector delivers fuel to more than one cylinder.
Multipoint - One fuel injector for each cylinder. These injectors are always used for diesel engines.
Mechanical - Fuel is metered by a mechanical pump, throttle linkage, or actuation of a cam.
Electronic - Fuel supplied by the use of a computer and various sensors.
Port - The fuel injector sprays into the air stream at the intake port upstream from the cylinder.
In-cylinder - The fuel injector sprays directly into the cylinder.
Low Pressure - Fuel is injected at a pressure close to intake pressure.
High Pressure - Fuel is injected near the end of the compression stroke when the pressure is close to the compression pressure.
Timed or Pulse - Each injection has a finite duration. Each injection is timed to begin and end at specific times in the cycle.
Continuous or Steady - Fuel is flowing through the injector during all parts of the engine cycle. Fuel is metered by the pressure upstream of the injectors.
Hydraulic - Fuel injection that uses air or fuel pressure to move control devices.
Throttle-body injector - A fuel injection system that has the injectors located in an assembly with the throttle plates. The injectors spray down into the plate area.

Antechamber Prechamber

Fuel can also be injected into antechamber or prechamber of an engine (Fig. 205.13). The prechamber has one or two small holes in it that are open to the main combustion chamber enclosed by the piston and cylinder. In Otto cycle engines the electrode of the spark plug is in the upper portion of the prechamber. Fuel is injected into the prechamber and the rest of the combustion chamber so that the mixture in the prechamber is relatively rich and the rest of the combustion chamber is lean. The rich mixture in the prechamber helps get the flame front from combustion started. The lean mixture in the rest of the cylinder can then burn. The prechamber design helps reduce pollutant emissions.

Figure 205.13 illustrates a prechamber system for a SI engine using a gaseous fuel. A gas valve injects fuel into the prechamber and another gas valve injects fuel into the incoming air, forming a very lean mixture in the intake of the engine. A mixing vane is used to provide turbulence to mix the air and fuel well. The lean air/fuel mixture enters the combustion chamber through the main valve for the cylinder.

Direct/Indirect Injection

Injection into a prechamber is sometimes also referred to as indirect injection. Therefore, direct injection would simply mean fuel injection into a typical combustion chamber or cylinder. This is also called an open chamber engine, since combustion takes place in an open volume bounded by the cylinder walls, the cylinder head and the piston.

205.8.3 Diesel Injectors

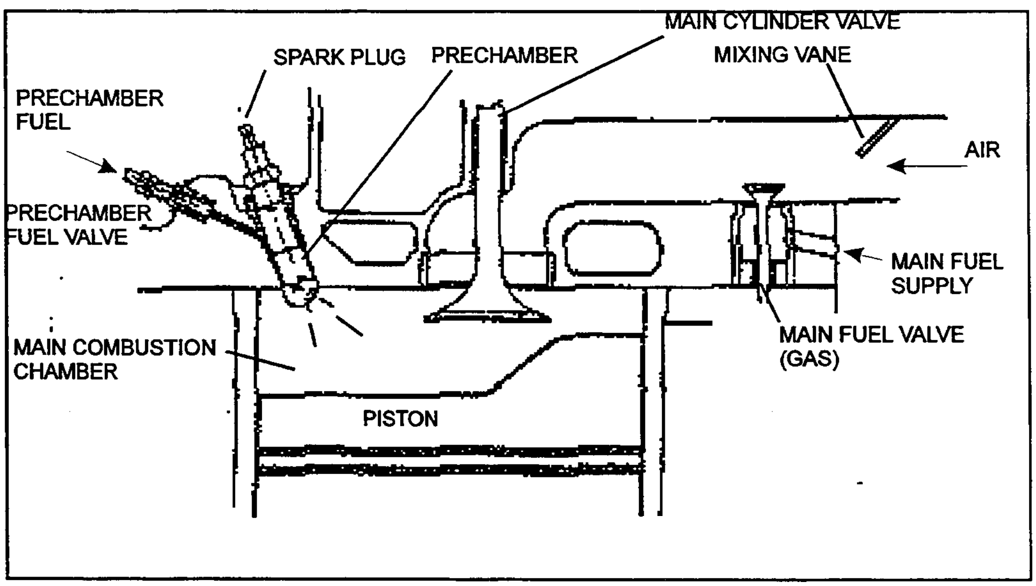

Figure 205.13 Prechamber for a Gas Engine

Fuel injectors are the heart of a diesel engine since the performance of the engine depends heavily on properly functioning injectors. The operation of fuel injectors is very complicated. They are expensive and are manufactured with great accuracy. Injectors for diesel engines are built more strong and durable because of the high compression ratios. Different fuel injector designs exist, but they can be divided into two main categories: air injectors and solid injectors.

Air Injectors

Air injectors use compressed air to force fuel into the cylinder. This type of system is rarely used, but it can provide very good mixing of fuel and air and it works well with fuels of high viscosity.

With solid injectors the fuel is pressurized to force it into the cylinder. Some of the main parts in the system include the high pressure pump, injector, check valve, and the injector nozzle. The high pressure pump pressurizes the fuel and the injector delivers the fuel to the cylinder. A check valve prevents fuel from flowing backwards in the system from the high pressures developed in the cylinder.

Solid Injectors

Solid injector systems can be categorized by the location of fuel pumps and injectors, the method of actuating fuel pumps, and the method used to meter fuel. Some of these systems include the common rail, unit injector, individual pump and nozzle, and multiple pump.

Common Rail System

The common rail system has a pump that supplies fuel at high pressure to a common rail or fuel header. The header then supplies fuel to injectors at each of the engine's cylinders through metal tubing. The injector can be opened mechanically by a cam, follower, push rod, or rocker arm, or it can be controlled electronically. The mechanical system operates similar to the mechanism for the intake and exhaust valves. In the mechanical system, the amount of fuel delivered may be controlled by the length of the pushrod movement. The fuel injection may also be controlled electrically. A computer can be used calculate the amount of fuel that should be injected and the timing of the injection.

Unit Injector

In the unit injector, both the fuel pump and injector are within one housing (Fig. 205.14). The system may also include an additional low pressure fuel pump feeding all the injectors for the engine. In the mechanically actuated fuel injector, the amount of fuel delivered is controlled by the amount of stroke of the plunger.

In the individual pump and nozzle fuel injection system, each cylinder of the engine has one pump and one injector, and this pump and the injector are separate from each other. The injector may be in the cylinder head while the pump could be on the side of the cylinder. In some designs all the fuel pumps may be arranged in a cluster. Figure 205.14 illustrates a multiple pump injector.

The nozzle tip of an injector distributes the fuel from the injector into the cylinder. For liquid fuels, the nozzle converts the liquid into fine droplets. It must atomize the fuel to help mix the fuel and air without impinging liquid fuel on the walls of the cylinder or the top of the piston. Any fuel that strikes the walls can cause it to decompose and form carbon deposits. Excessive smoke emissions, odors and increased fuel consumption may result.

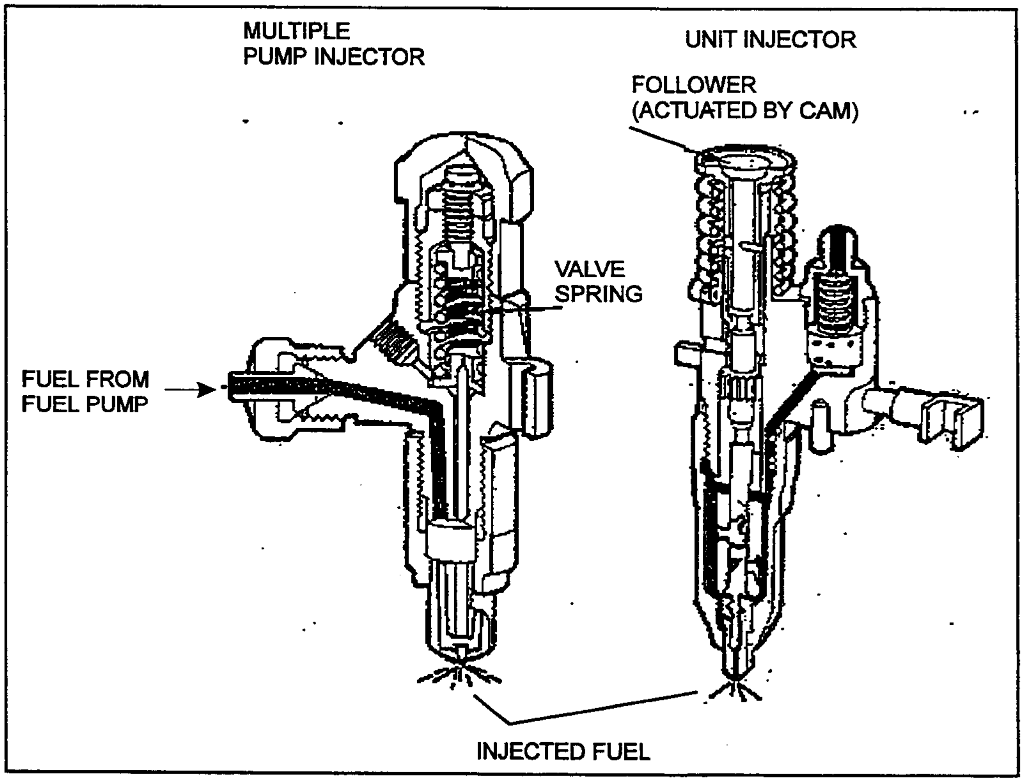

Figure 205.14 Diesel Injectors

Fuel Atomization

The injection pressure, the density of the air in the cylinder and the physical characteristics of the fuel are also important factors for proper atomization.[26] Higher injection pressures improve dispersion of the fuel within the combustion chamber and cause liquid fuels to be atomized into smaller droplets. This will help improve the mixing of fuel and air. When the density of the air in the cylinder from compression is higher, the resistance against fuel droplets traveling across the cylinder increases, but dispersion of the fuel is improved. The surface tension and viscosity of the fuel are physical characteristics that affect the dispersion of the fuel.

The type of nozzle tip used depends on the design of the combustion chamber. Turbulence required to mix fuel and air may be dependent on the design of the combustion chamber or it may be dependent on the nozzle of the fuel injector and the injection pressure. In a combustion chamber with low turbulence, a nozzle and injection pressure producing better mixing must be chosen. No single nozzle is ideal for all engines. A nozzle may work well in one engine, but not in another. The nozzle must be fitted to the correct combustion chamber.

Different nozzle tip designs exist; some of these include the single orifice, multi-orifice, and the pintle type. The single orifice has a nozzle with a single hole, and the multi-orifice design has several drilled holes to inject fuel. The pintle type has a plunger in the fuel passageway to control the flow of the fuel. The orifices in the nozzle tips are very small and may get clogged. Single and multiple orifice nozzles tend to be more prone to clogging. The pintle type nozzle is a design that is less prone to clogging because of its plunger design. Impurities in the fuel and carbon particles from combustion can cause clogging. A clogged injector will disrupt the flow of fuel into a cylinder and can reduce the power output and performance of the engine.

205.9 RECIPROCATING ENGINE FUELS

A wide range of fuels can be used to run reciprocating engines, including: natural gas, different grades of refined petroleum, coal-derived gases, and waste gases such as landfill or sewage digester gas. Natural gas is the main fuel used to run large sized stationary reciprocating engines. Natural gas is primarily composed of methane (CH_4), but it also contains ethane (C_2H_6) and smaller amounts of other gases.

Gasoline and diesel are the two main fuels produced from refined petroleum that are used to run reciprocating engines. Heavy fuel oil has also been used in some diesel engines on a limited basis. Gasoline is primarily used to run mobile and portable spark ignition engines which are used at construction sites, farms and households in small and medium-sized stationary applications. These engines may often be converted mobile engines, so parts, service and the gasoline fuel are readily available. Diesel engines have a higher efficiency than spark ignition engines, so it is more practical for large engines to be diesel. Diesel fuel is readily available and many diesel engines are used in stationary applications.

The hydrocarbons (compounds of hydrogen and carbon) that make up gasoline are in the C4 to C12 range and the boiling points for these hydrocarbons range from 100°F to 400°F. Many of the hydrocarbon fractions from crude oil are refined to make gasoline, including straight run or natural gasoline, naphtha, kerosene, and gas oil. The boiling points of these fractions and others are shown in

Table 205.1.[27] The lighter components in gasoline vaporize more readily at lower temperatures and allow an engine to be started under cold weather conditions. When the engine is hotter during the summer months and/or at high altitudes, the heavier components help prevent vapor lock due to excessive vaporization of the fuel. When vapor lock occurs, vapors form in the fuel system. The fuel pump is only designed to handle liquid, so the engine is starved of fuel and may not start.

Vapor Lock

Table 205.1 Crude Oil Fractions and Boiling Points

Fraction	Boiling Point (Degrees F)
Butanes and lighter	Less than 90
Gasoline	90-220
Naphtha	220-315
Kerosene	315-450
Gas oil	450-800
Residue	800 and higher

Waste gases such as digester gas and landfill gas can also be used to fuel reciprocating engines. Digester gas and landfill gas are primarily made of methane, so they are used similar to natural gas. These gases may be mixed with natural gas from a utility. Digester gas is acquired from waste water or sewage treatment, and landfill gas is gathered from rotting garbage at a landfill.

205.9.1 Knock and Preignition

Autoignition

"Knock" is any unusual sound that arises because of autoignition during the normal combustion process. Autoignition occurs when a portion of the fuel charge spontaneously ignites without a separate ignition source. Autoignition occurs if the temperature and pressure of any portion of the fuel charge exceeds the self-ignition conditions for the air and fuel mixture being burned. Knock is perceived as a thud or ping coming from the engine.

Detonation

A more technical term that is a synonym used to describe knock is detonation. Knock can be divided into two categories, including nonexplosive, very rapid burning where a ping would be audible, and explosive burning which results in heavy knock or thudding. Since knock or detonation occurs without an ignition source, the increase in pressure from knock can occur at the wrong time and may occur before the piston reaches the top of the cylinder, working against the motion of the crankshaft. Besides causing a loss in power, knocking vibrates the engine's part and in severe cases it can damage the pistons or bearings in an engine.

An example comparison between normal combustion and rapid burning is possible with gunpowder. Combustion of an air/fuel mixture in a cylinder takes approximately 3/1,000 of a second to burn, but an equal amount of gunpowder only takes about 1/50,000 of a second to burn. Gunpowder burns 150 times faster than the air/fuel mixture in the cylinder of an engine.[28]

The occurrence of detonation depends on compression ratio, the type of fuel, the air/fuel ratio, ambient conditions, engine load, engine speed and other variables. Some engines have systems to make adjustments to the engine when detonation is detected, to prevent damage. The ignition timing may be automatically retarded to prevent detonation and the engine may even shut itself off.

Preignition

Preignition (premature ignition) is defined as combustion that starts from a hot spot in the combustion chamber before normal ignition occurs. Preignition can start from an excessively hot carbon deposit in the cylinder, an excessively hot valve, a jagged edge in the combustion chamber, or a low octane fuel. Severe preignition can even cause an engine to run after the ignition has been turned off. This is also called "dieseling." If the hot spot causing preignition is near a spark plug, combustion may appear to be normal, but it will have the same characteristics as advanced ignition timing. Excessive heating of the spark plug tips from detonation can cause preignition.

Dieseling

Severe preignition can also cause loss of power and fuel economy, poor engine operation, and may damage the engine. Overheated carbon deposits in the cylinder can cause preignition. Preignition can also lead to detonation or knock.

205.9.2 Octane and Cetane Number

The octane number of gasoline is a measure of its resistance to knock in an engine. The higher the octane number is, the more resistant to knock, and the more expensive the fuel will be. Isooctane, C_8H_{18}, is defined as 100 octane and normal heptane, C_7H_{16}, which has a much greater tendency to knock and therefore knocks at a much lower compression ratio, is defined as zero octane. By using a test engine, the knocking characteristics of any gasoline can be matched with blends of isooctane and normal heptane. The octane number of a fuel is equivalent to the percent of isooctane in an isooctane/N-heptane blend that knocks at the same compression ratio as the test fuel.

Diesel fuel has a higher molecular weight and energy content than gasoline. Diesel is made from fractions in the light gas oil range (Table 205.1). Self ignition of diesel fuel is a quality that is desired. The cetane number is a measure of the ignition quality of the fuel. The cetane number is the percent cetane ($C_{16}H_{34}$) in a mixture of cetane and alpha-methylnaphthalene.[29] When this mixture has the same ignition characteristics in a test engine as the diesel fuel, the diesel fuel has a cetane number equal to that percent cetane. Regular diesel has a cetane number of 40 to 50, and premium diesel has a cetane number of 45 to 50. The premium fuel will have more volatile components, will be better for cold starts, and will tend to smoke less. Fuels with higher cetane numbers have lower self-ignition temperatures and a shorter ignition delay period. Fuels with lower cetane numbers will tend to make an engine run rougher. The cetane number is partly a function of the paraffin, olefin, naphthalene, and aromatic content (also called PONA).

206 ENGINE POWER AND PERFORMANCE

Power is defined as the rate of doing work. Work is the force exerted times the distance over which it is applied and it is usually in units of ft-lbf (foot-pounds force).

W = (d)F
where:
W = Work (ft-lbf)
F = Force (lbf)
d = Distance (ft)

If, for example, an object was pushed one foot by applying a force of 550 lbf, the work done is: W = (1 ft)(550 lbf) = 550 ft-lbf
Furthermore, power is the time rate of doing work.

P = W/t
where:
t = time (seconds)
P = Power (ft-lbf/sec)

If the work in the above example is done in one second, the power is:
P = 550 ft-lbf/1.0 sec = 550 ft-lbf/sec. One horsepower is equivalent to 550 ft-lbf/sec, therefore the power can be stated in horsepower:

P = (550 ft-lbf/sec)/(550 ft-lbf/sec) = 1 hp.
The power can also be stated in terms of British Thermal Units (Btu), since 778 ft-lbf are equivalent to 1.0 Btu: P = (550 ft-lbf/sec)(1 Btu/778 ft-lbf) = 0.707 Btu/sec.

Thermal Efficiency

There are three main categories of engine power from an engine, including the indicated horsepower (IHP), brake horsepower (BHP), and the friction horsepower (FHP). Figure 206.1 illustrates these types of energy.[30] As the fuel is delivered to the engine, all of the energy is in the fuel in terms of potential energy. When the fuel burns in the cylinder, the chemical energy of the fuel is converted to heat. Some energy is lost by heat through the cylinder walls, coolant and from the exhaust. Most of the rest of the energy goes toward moving the piston down the cylinder. This energy is the indicated horsepower. The ratio of energy delivered to the piston to the energy contained in the fuel is called the indicated thermal efficiency.

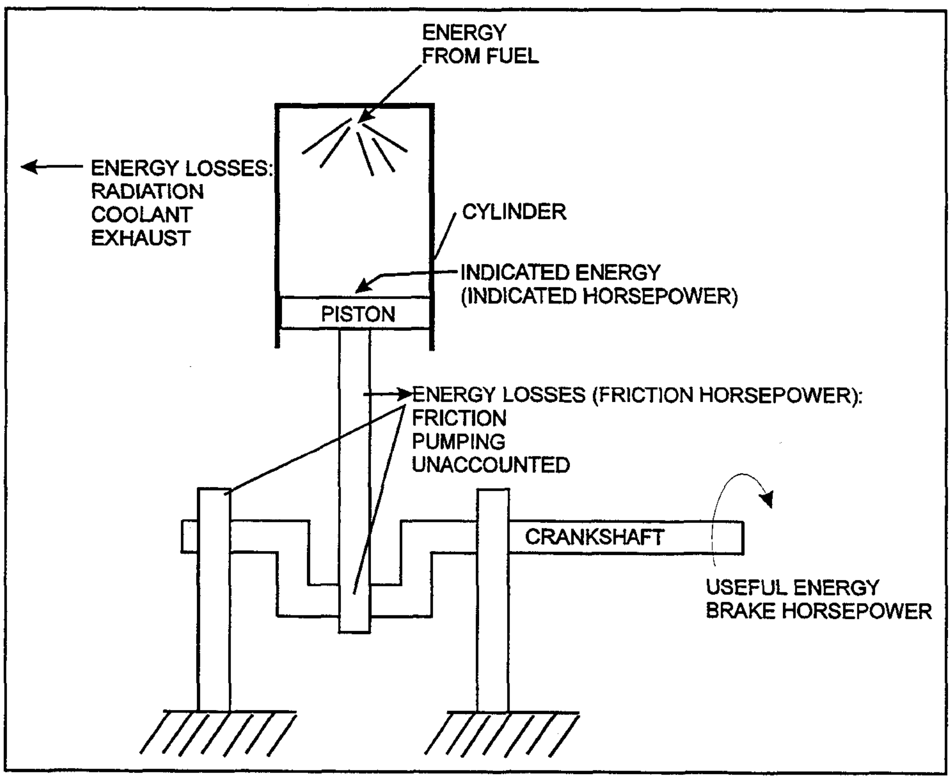

Figure 206.1 Engine Energy Flow IHP, FHP, and BHP

The energy delivered to the piston passes through the connecting rod to the crankshaft, and out through the driveshaft. As this occurs, energy is lost from friction in the bearings between the connecting rod and piston, and between the crankshaft and the connecting rod. Energy is also lost from the pumping action of the piston. These losses and others between the piston and driveshaft are called the friction horsepower (FHP). The remaining power available to do work (i.e. run a pump or turn a generator to create electricity) is the brake horsepower. The brake horsepower can also be referred to as the shaft horsepower or delivered horsepower. The ratio of the brake horsepower to the indicated horsepower is called the mechanical efficiency. Furthermore, the brake horsepower is equal to the difference between the indicated horsepower and the friction horsepower. Figure 206.2 illustrates the approximate percentages of energy losses and useful energy from the fuel in an engine.

Brake Horsepower

$\eta_{mech} = Bhp/Ihp$
$Bhp = Ihp - Fhp$
$\eta_{It} = Ihp/Qin$
$\eta_{Bt} = Bhp/Qin$

Mechanical Efficiency

Where:
η_{mech} = Mechanical efficiency
Bhp = Brake horsepower
Ihp = Indicated horsepower
Fhp = Friction horsepower
η_{It} = Indicated thermal efficiency
η_{Bt} = Brake thermal efficiency

206.1 MEAN EFFECTIVE PRESSURE

The mean effective pressure is essentially a mean value of the pressure in the cylinder of an engine, such that when multiplied by the displacement, the result is the work.[31] It is usually in units of (lbf/in^2) or (psi).

$$W(lbf\text{-}ft) = [Mep(lbf/in^2)][V_d(in^3)][1ft/12in]$$

Where:
Mep = Mean effective pressure (lbf/in^2)
W = Work output (lbf-ft)
V_d = Displacement (in^3)

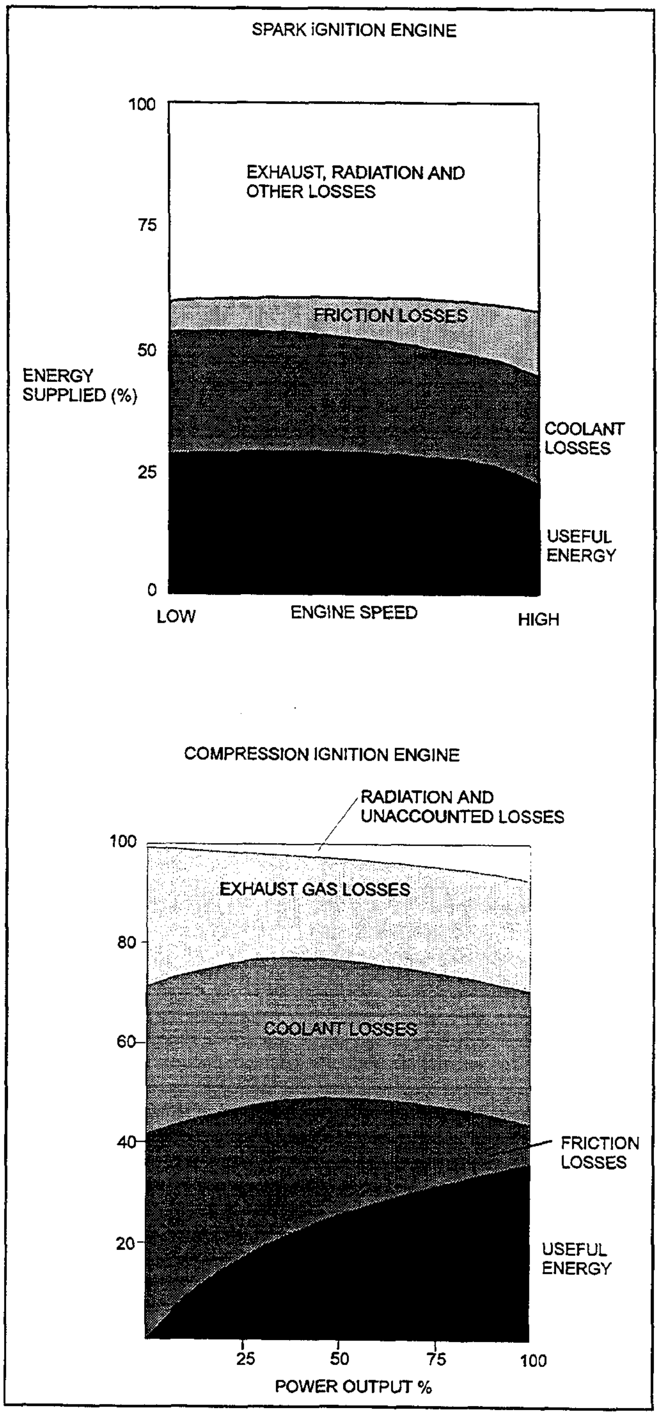

Figure 206.2 Heat Balance of a Spark Ignition and a Compression Ignition Engine

As with horsepower, mean effective pressure can be described as the indicated mean effective pressure, brake mean effective pressure or friction mean effective pressure. The value of the indicated mean effective pressure comes from the ideal P-V diagram (Fig. 206.3).[32] The pressure in the cylinder varies drastically as the engine goes through its power cycle 1-2-3-4, but a rectangle A-B-C-D can be drawn with an area equivalent to the area of 1-2-3-4. The distance between AB and CD represents the indicated mean effective pressure (Imep). The brake mean effective pressure (Bmep) is a pressure value which represents the portion of the Imep that is used to produce useful work.[33] The friction mean effective pressure (Fmep) is the portion of the Imep that is used to overcome the friction losses in the engine. Relations similar to those for horsepower can be developed for the mean effective pressure.

$\text{Bmep} = \text{Imep} - \text{Fmep}$
$\eta_{mech} = \text{Bmep}/\text{Imep}$

Bmep = Brake mean effective pressure
Imep = Indicated mean effective pressure
Fmep = Friction mean effective pressure
η_{mech} = Mechanical efficiency

206.2 SPECIFIC FUEL CONSUMPTION

The specific fuel consumption (Sfc) is the mass flow rate of the fuel used by an engine divided by its horsepower. For liquid fuels the mass flow rate of the fuel is usually in (lbm/hr), so the units of specific fuel consumption are (lbm/hp-hr). For gaseous fuels the fuel consumption is usually in Btu/hr or Btu/hp-hr. The specific fuel consumption is one of the most important parameters for comparing the power output of different engines.

As with other parameters the specific fuel consumption can be calculated in terms of the brake or indicated horsepower. If the indicated horsepower is used to find the specific fuel consumption, it is the indicated specific fuel consumption (Isfc), and if the brake horsepower is used to find the Sfc, it is the Brake specific fuel consumption (Bsfc).

$\text{Isfc} = m_f/\text{Ihp}$ or q/Ihp
$\text{Bsfc} = m_f/\text{Bhp}$ or q/Bhp
Isfc = Indicated specific fuel consumption (lbm/hp-hr or Btu/hp-hr)

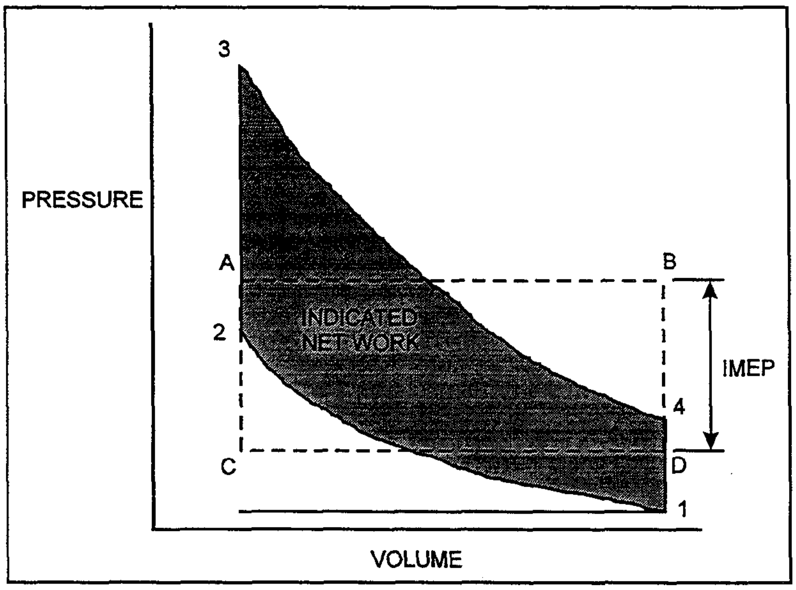

Figure 206.3 Graphical Illustration of IMEP on P-V Diagram

Bsfc = Brake specific fuel consumption (lbm/hp-hr or Btu/hp-hr)
m_f = Mass flow rate of fuel (lbm/hr)
q = Rate of heat input from gaseous fuel (Btu/hr)

206.3 CALCULATING INDICATED AND BRAKE HORSEPOWER

A common method of calculating the indicated horsepower at full throttle is by use of the "PLAN" formula:

Ihp = PLAN/33000

Where:
P = Indicated mean effective pressure (psig)
L = Stroke (feet) [the distance of piston travel]
A = Area (in^2) [the area of the top surface of the piston]
N = $[(2n)(c)]/n_s$ [The number of power strokes per minute]
 n = Engine speed (rpm, i.e. revolutions per minute)
 c = The number of cylinders
 n_s = The number of strokes per cycle (i.e. 2 or 4)

Dynamometer

In order to determine the brake horsepower output of an engine, a device such as a dynamometer must be connected to the drive shaft. A dynamometer is a device that puts a load on an engine, allowing the speed of an engine to be controlled. The dynamometer can measure an engine's power output and other parameters at different speeds. Modern dynamometers can instantly compute the horsepower output and other performance parameters of an engine at different rotational speeds.

Prony Brake

A description of the "classic" Prony brake helps illustrate the principles of brake horsepower and the brake horsepower formula. The Prony brake consists of a flywheel attached to the driveshaft of the engine, an adjustable friction band connected to an arm, and a scale (Fig 206.4).[34] When the band is tightened around the flywheel, friction develops between the band and flywheel. The friction force tends to make the arm rotate and pull against the scale. The band puts a load on the engine and the scale is a means of measuring it. The following expression can be developed for calculating the brake horsepower from the rotational speed and force measured by the prony brake:

$$Bhp = [2\pi(R)F(rpm)]/33000$$

where:
Bhp = Brake horsepower

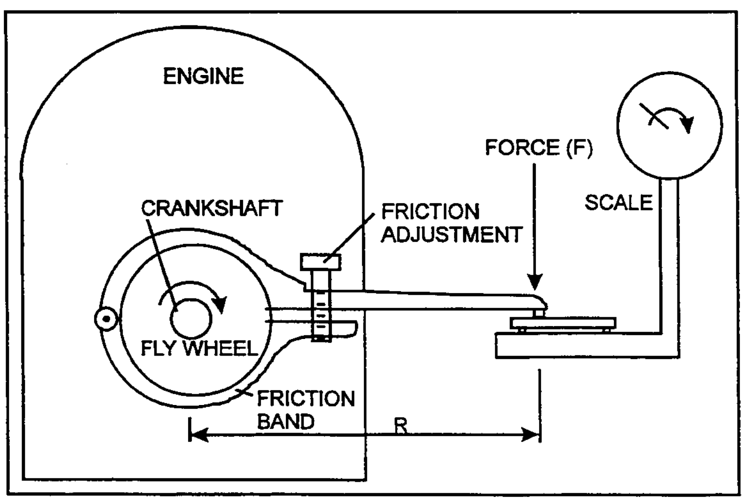

Figure 206.4 Prony Brake

R = Distance from center of flywheel to location of force measured with scale or the "moment arm" distance (ft)
F = Force measured by scale on prony brake (lbf)
RF = Brake torque (lbf-ft)
rpm = Rotational speed of crankshaft (revolutions per minute)

The above equation can also be changed to calculate the brake torque:

RF = Brake torque = T
$T = [(33000)Bhp]/2\pi(rpm)$

The specific fuel consumption can also be used to calculate the engine horsepower. Depending on whether the indicated or brake specific fuel consumption is used, the indicated or brake horsepower can be calculated:

$hp = m_f/Sfc$

where:
hp = Horsepower
m_f = Mass flow rate of fuel (lbm/hr)
Sfc = Specific fuel consumption (lbm/hp-hr)

206.4 INDICATOR DIAGRAM AND PERFORMANCE

Figure 206.5 illustrates how the indicator card varies for a spark ignition engine at full throttle and part throttle. Note how the area "A" of the indicator card at full throttle has a larger area than the indicator card at part throttle. This shows that the work output of the engine is higher at full throttle. Area "A" indicates positive work and area "B" indicates negative work. Area "B" of the indicator card is smaller for the engine at full throttle, so this shows that the pumping losses are smaller at full throttle. While area "A" shows the indicated horsepower, area "B" is part of the friction horsepower.

Area "B" (the pumping loop) is larger at part throttle because of the restriction of the flow of fresh air and fuel into the cylinder. When the throttle is partially closed the charge cannot flow as rapidly into the cylinder to fill the increasing volume above the piston. This causes the pressure in the cylinder to lower during the intake stroke. By examining the indicator diagram it can be seen that lowering the pressure during the intake stroke lowers the line on the bottom of the pumping loop, so the area of the pumping loop is larger.

From Figure 206.5 it can also be seen that the ignition point is before top dead center on the compression stroke. The maximum pressure from combustion then occurs after top dead center. This is illustrated more clearly in the pressure versus crank angle diagram (Fig. 206.6).[35] From Figure 206.6 it is more apparent that it takes time for combustion to occur. The maximum pressure doesn't occur until a period of time after ignition and some rotation of the crankshaft.

In an actual engine the exhaust valve also opens early before bottom dead center (Fig. 206.5). This is necessary because it takes time for the exhaust valve to open and to get the flow of the exhaust gases started. If the exhaust valve did not open until bottom dead center, the pressure inside the cylinder would be higher during the exhaust stroke and the "negative" pumping stroke loop would be larger in area. This would then cause a decrease in the net output work of the cycle. On the other hand, opening the exhaust valve early causes a decrease in the pressure in the cylinder at the end of the power stroke. This causes a decrease in the work output from the power stroke, but when the pumping loop is taken into account, the overall effect on the output work is higher with the exhaust valve opening early.

Figure 206.7 illustrates what happens to the indicator diagram when the spark is retarded (moving the spark closer to top dead center).[36] Because of the time required for combustion, retarding the spark also makes the peak pressure occur at a later time. When the peak pressure occurs, the piston is closer to bottom dead center, so the peak pressure is lowered. This reduces the area of the indicator diagram and the work output of the cycle.

Advancing the spark also advances the time when the peak pressure occurs. Since this is closer to top dead center, the peak pressure is higher, but work output is reduced since the area of the indicator diagram is reduced (Fig. 206.7).[37]

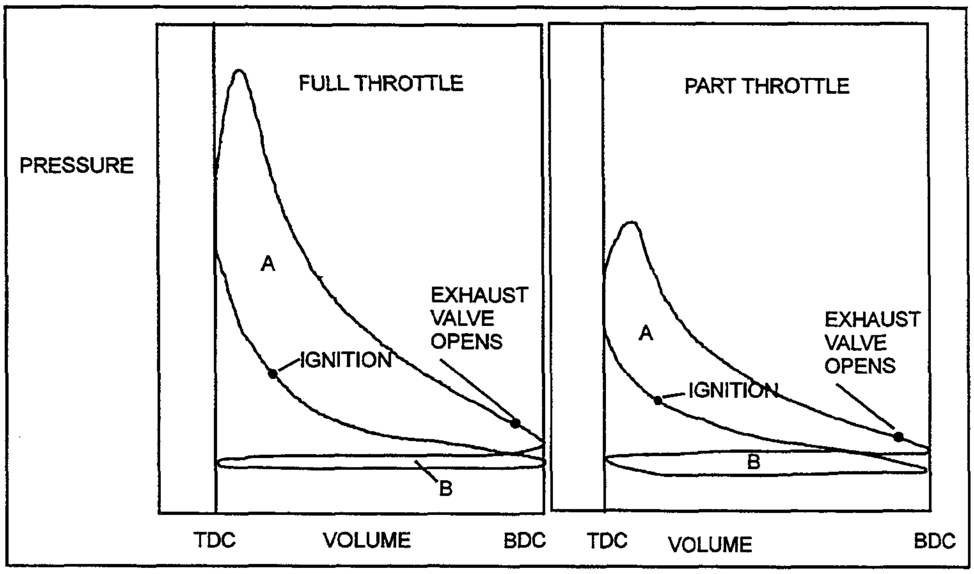

Figure 206.5 Affect of Throttle on Indicator Card

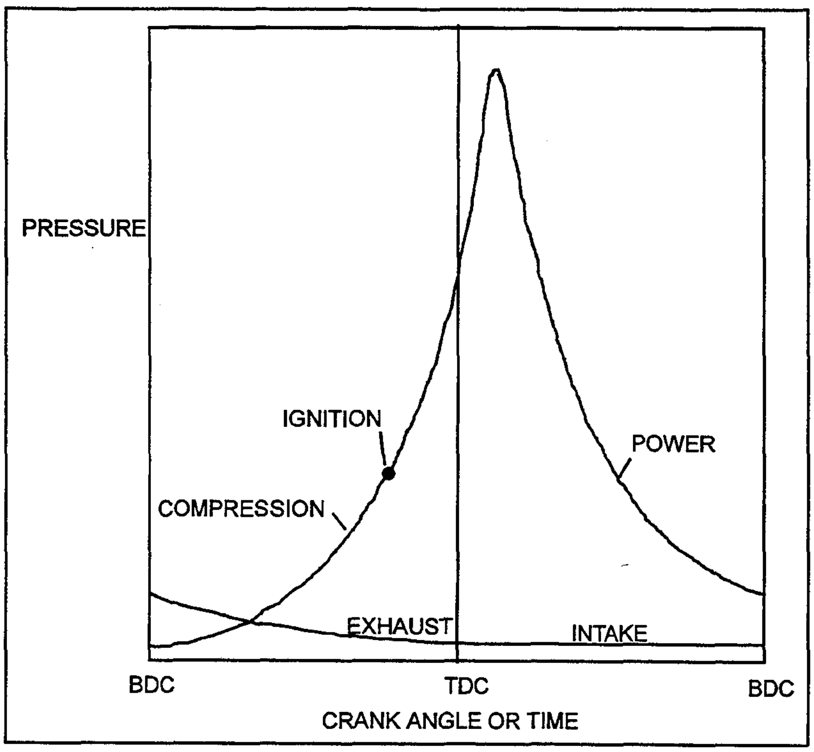

Figure 206.6 Pressure vs. Crank Angle

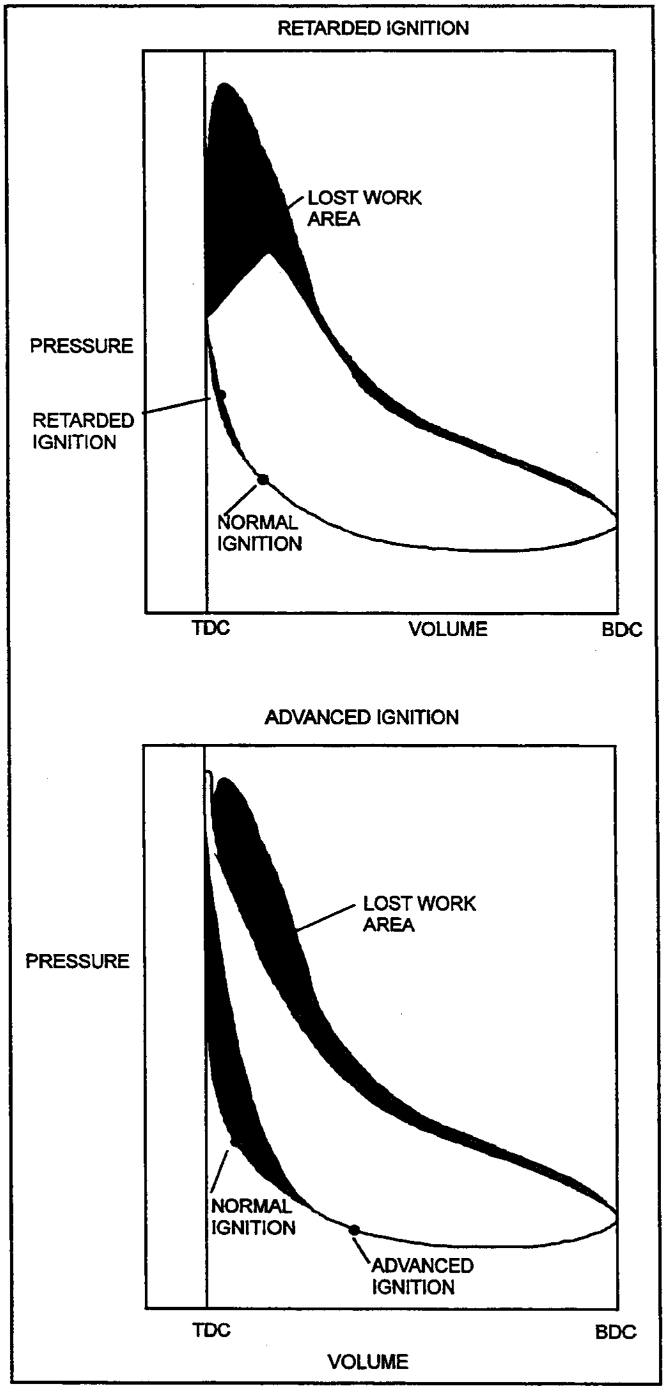

Figure 206.7 Effect of Retarded and Advanced Ignition on Indicator Diagram

206.5 VOLUMETRIC EFFICIENCY

The output of a spark ignition engine is highly dependent on the amount of energy released during combustion. There is a restricted range of air to fuel ratios that will provide good combustion, and the volume of air used is much larger than the volume of fuel. Therefore, the output of the engine is highly dependent on the amount of air that can be put into the engine. The more air that can be put into an engine, the more fuel that can be added to increase the energy released by combustion, and the more work output will be produced.

The volumetric efficiency is a measurement of how well air is being put into an engine. It is the ratio of the actual mass of air drawn into the engine during a given time period, to the theoretical mass which should have been drawn in during the same time period, based on the total displacement of the engine, and the temperature and pressure of the atmospheric air. Therefore:

$e_v = m_{act}/m_{theo}$

e_v = Volumetric efficiency
m_{act} = Actual mass of air drawn into cylinder per unit time
m_{theo} = Theoretical mass of air drawn into cylinder per unit time
$= [(N)(V_d)(\rho)]/[(n)1728]$
where:
N = Rpm (revolutions per minute)
V_d = Total displacement (in^3)
n = Revolutions per intake stroke
ρ = Air density (lbm/ft^3) [about 0.075 lbm/ft^3 at 70° F]

Some of the main items that may affect the volumetric efficiency include: the density of the fresh air charge after it enters the cylinder; the temperature and pressure of the exhaust in the clearance volume; the timing of the valves; and the design of the valves, intake manifold, and exhaust manifold. When fresh air enters the cylinder it is heated by the hot cylinder walls. This decreases the density of the fresh air charge, so the volumetric efficiency is also decreased. The volumetric efficiency will tend to be higher with air charges that are lower in temperature and higher in pressure. Lower temperatures and higher pressures increase the density of the air.

The hot exhaust products in the clearance volume increase the temperature of the fresh air charge and decrease volumetric efficiency. Exhaust in the clearance volume will tend to expand and occupy more of the cylinder when the piston moves downward. This reduces the volume available for the fresh air charge and decreases the volumetric efficiency.

An engine with four valves per cylinder (two intake and two exhaust valves) will generally have a higher volumetric efficiency than an engine with two valves per cylinder (one intake and one exhaust valve). Due to the velocity of the air entering a cylinder when the piston is on its downward stroke, the inertia of the air still continues to cause air to flow in the cylinder a short period of time after bottom dead center when the piston is moving upward. In higher speed engines, the intake valves are timed to close with a larger time period after bottom dead center than lower speed engines, because the air entering the engine will have greater inertia from the higher speed of the piston. Timing the intake valve in this manner helps improve volumetric efficiency.

Valve Overlap

In a similar manner the timing of the exhaust valves can improve volumetric efficiency. This can be done by delaying the closing of exhaust valves after top dead center. The inertia of the exhaust flow after the piston reaches top dead center will tend to scavenge the cylinder by carrying out more exhaust gases. Sometimes intake and exhaust valves are timed so that they are open at the same time. This is called valve overlap. The duration of valve overlap must not be excessive so that exhaust gases are not sucked into the intake manifold, and none of the fresh charge escapes out the exhaust valve.

206.6 PERFORMANCE CURVES

Figures 206.8 and 206.9 illustrate typical performance curves of a spark ignition engine.[38] The curves are a graphical representation of the engine's performance (including torque, horse power, and specific fuel consumption) at different rotational speeds. They are good for comparing the performance of different engines.

Within the speed range of an engine, there is a speed where the charge per cylinder for every power cycle is largest. At this point the largest mass of air is put into the engine on every intake stroke and the highest force from combustion is put on the piston. This point also tends to be the highest point on the torque curve.

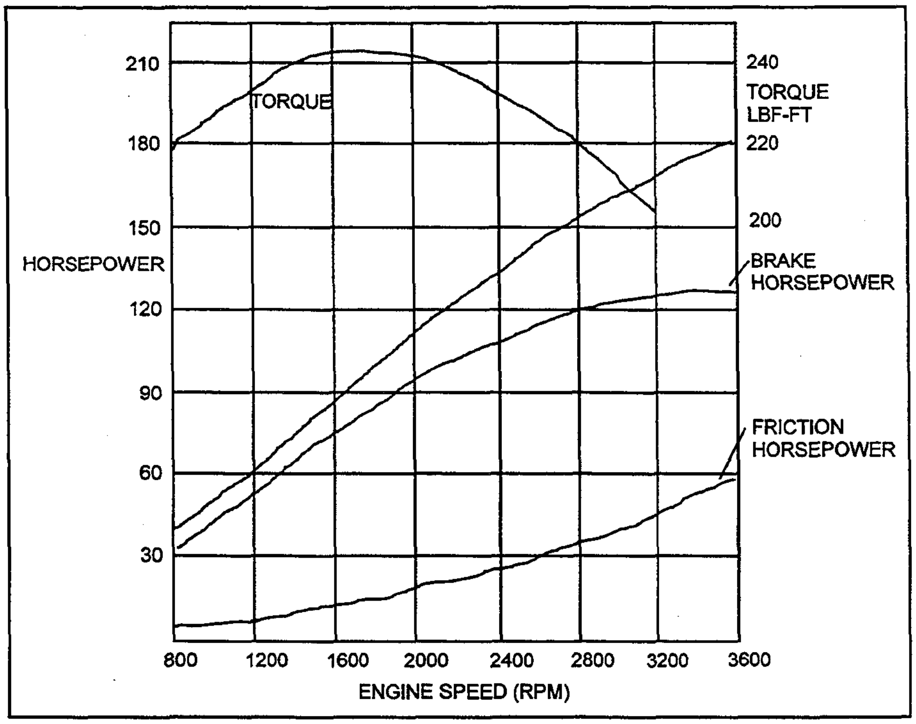

Figure 206.8 Performance Curves (SI Engine at Full Throttle)

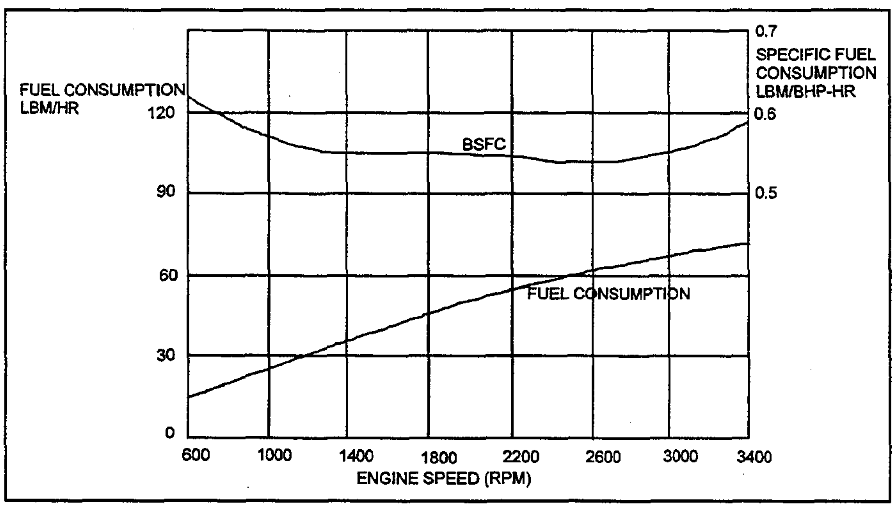

Figure 206.9 Fuel Consumption vs. Engine Speed (SI Engine at Full Throttle)

As the speed of an engine is increased above the speed where the maximum amount of air is delivered per cycle, the amount of air entering the cylinder per cycle will decrease. On the other hand, since there are more strokes of the engine during a given amount of time, the engine consumes more air over a given amount of time. Air consumption will continue to increase with engine speed until the decrease in the amount of air that enters the cylinder on each intake stroke exceeds the increase in the number of strokes per unit time. The maximum indicated horsepower will generally correspond to the point where air consumption per unit time is maximum.[39]

As the engine speed increases, the indicated horsepower and air consumption increase to a maximum value, but the friction horsepower will also increase (Fig. 206.9). The friction horsepower is low at the lowest speeds, so the brake horsepower is nearly equivalent to the indicated horsepower at this point.

The brake specific fuel consumption tends to be higher at low and high speeds, but it levels off at moderate speeds. At low speeds the portion of heat loss to the cylinder is higher and the efficiency is lower, so the brake specific fuel consumption is higher because the fuel use per power produced is higher. At high speeds the increase in brake specific fuel consumption is due to the increase in friction horsepower.

Figure 206.10 shows performance curves for a compression ignition engine. This figure shows maximum power for different conditions. Curves labeled with a "1" are "laboratory" performance or the maximum possible power output. Curves labeled with a "2" are maximum power output with intermittent operation. Curves labeled with a "3" are maximum power for a continuous operating service.

206.7 ENGINE PERFORMANCE

The main variables that affect the performance of an Otto cycle engine are the combustion rate and spark timing, compression ratio, air/fuel ratio, engine speed, heat losses, and the weight of the inducted charge.[40]

The occurrence of the spark is generally timed so the maximum pressure from combustion occurs as close as possible to the beginning of the power stroke.

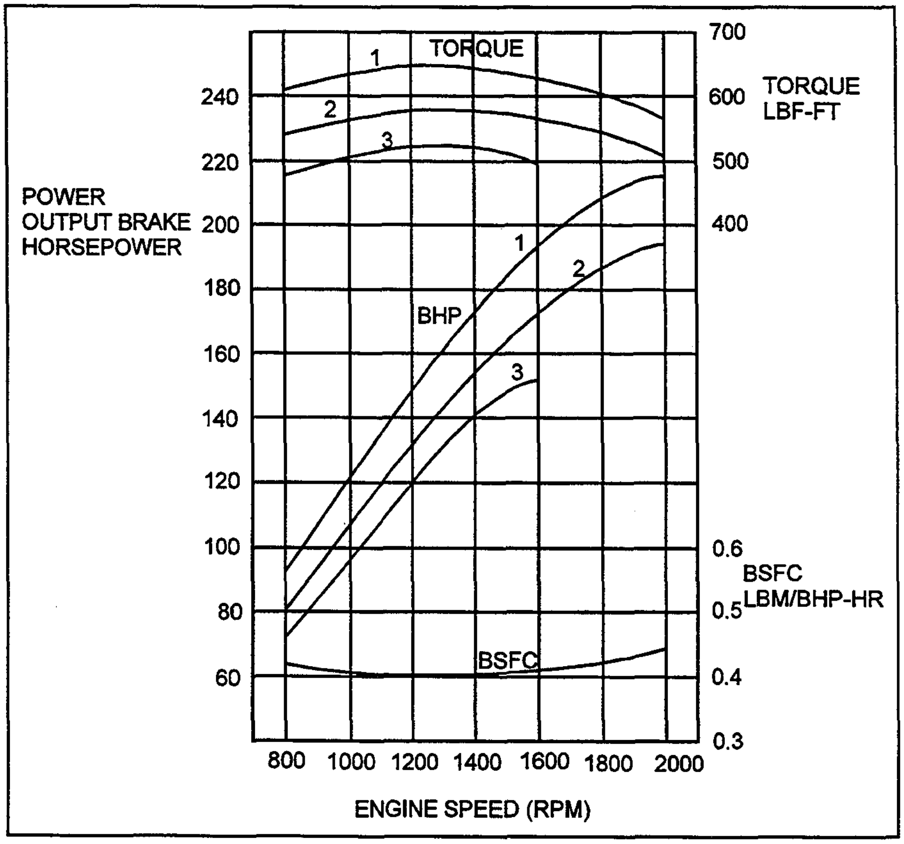

Figure 206.10 Performance of Four Stroke, Six Cylinder Compression Ignition Engine

In general, the higher the compression ratio, the higher the efficiency will be. The compression ratio is limited by detonation or "pinging." Higher octane fuels make the use of higher compression ratios possible. Detonation can do serious damage to an engine.

At lower engine speeds a larger portion of heat escapes through the walls of the cylinder. At high speeds the friction horsepower gets higher and tends to decrease efficiency. Between these two extremes is a speed where performance is maximized, but this speed tends to be above the medium speed of the engine's performance window.

300 EMISSION CONTROL

Stationary Reciprocating Engines

This section describes the emissions from reciprocating engines and how they are controlled.

301 RECIPROCATING ENGINE EMISSIONS

Air pollution emissions from reciprocating engines are almost exclusively from combustion, but there is a potential for emissions from the storage of the fuel for the engines. Combustion emissions from a reciprocating engine include nitrogen oxides (NOx), sulfur dioxides (SOx), carbon monoxide (CO), unburned hydrocarbons, and particulate matter. The storage of liquid fuels can be a potential source of emissions because volatile hydrocarbons or volatile organic compounds (VOCs) in the fuel can escape from storage and enter the atmosphere. Emissions from gaseous fuels may also be of concern. As with all combustion processes, reciprocating engines emit a large number of other compounds in small amounts and some of them are toxic.

Natural Gas

Methane

Natural gas is often used to fuel stationary reciprocating engines. It is usually delivered to a plant via a pipeline and generally isn't stored at a plant in large quantities. Methane (CH_4) is the main gas component in natural gas, and natural gas also contains various amounts of ethane (C_2H_6). Methane is a greenhouse gas but it is not considered to be a VOC. Ethane is not considered to be a volatile organic compound by the Environmental Protection Agency (EPA), and is exempt from reactive organic gas (ROG) classification by the Air Resources Board.

Petroleum distillates such as gasoline or diesel can also be used to run a reciprocating engine. The storage of gasoline is a source of volatile organic compounds emissions. Diesel fuel has a vapor pressure at ambient conditions that is low enough to prevent problems with VOC emissions.

301.1 NOX EMISSIONS

There are seven known oxides of nitrogen, including: NO, NO_2, N_2O, NO_3, N_2O_3, N_2O_4, and N_2O_5. But only nitrogen oxide (NO), nitrogen dioxide (NO_2) and sometimes nitrous oxide (N_2O) are produced in high enough concentrations to be considered pollutants. Ninety to 95% of the nitrogen oxides that form from a combustion process are in the form of nitrogen oxide (NO), but nitrogen oxide can later photochemically react to form nitrogen dioxide (NO_2). Nitrogen dioxide is a more reactive molecule. Nitrous oxide (N_2O) can also form from NOx control processes and is sometimes a concern.[1]

300 EMISSION CONTROL

NOx Forming Mechanisms

There are two main mechanisms in which NOx is formed in a reciprocating engine. The first mechanism is due to the nitrogen in the air. The second mechanism is due to the nitrogen in the fuel.

301.1.1 Thermal NOx

Ideally, engines would burn fuel with pure oxygen because the only emissions with complete combustion would be carbon dioxide and water. In the real world atmospheric air, which is mostly nitrogen, is used for combustion instead of oxygen, and the nitrogen will react with the oxygen in the air, forming NOx compounds. The reaction between atmospheric nitrogen and oxygen is especially prevalent at higher combustion temperatures. This NOx formation mechanism is called thermal NOx and it is sometimes referred to as the "fixation of atmospheric nitrogen."

Atmospheric air is composed of 78% nitrogen, 20.9% oxygen, and a 1% total of carbon dioxide, water vapor, argon, helium and a very small percent of other inert gases. For most combustion applications, all of the atmospheric components are grouped with nitrogen, making air composed of approximately 20.9% oxygen (O_2) and 79.1% nitrogen (N_2) by volume. In terms of mass, the atmosphere is approximately 76.85% nitrogen and 23.15% oxygen.

In perfect, ideal combustion the only exhaust products are carbon dioxide and water. When methane is burned with oxygen the following reaction occurs:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

Stoichiometric Combustion

One molecule of methane requires two molecules of oxygen to burn completely and will yield one molecule of carbon dioxide and two molecules of water. This is called stoichiometric combustion. The chemical reaction also indicates the volumes required for stoichiometric combustion. For example, one cubic foot (ft^3) of methane will require two ft^3 of oxygen to burn completely. When atmospheric air is used to burn a fuel, the nitrogen in the air also becomes a part of the chemical reaction and NOx compounds can form. Since one ft^3 of air is composed of approximately 0.209 ft^3 of O_2 and 0.791 ft^3 of nitrogen:

$$(2\ ft^3\ O_2)[1\ ft^3\ air/0.209\ ft^3\ O_2](0.791\ ft^3\ N_2/1\ ft^3\ air) = 7.57\ ft^3\ N_2$$

and 7.57 ft^3 N_2 from atmospheric air are involved in the chemical reaction for 2

ft^3 of O_2 oxygen burned from atmospheric air. This illustrates that a large amount of nitrogen is involved when air is used for any combustion process.

When combustion occurs in the cylinder of an engine, nitrogen and oxygen molecules, which are normally in the form of N_2 and O_2, dissociate into free atoms at elevated temperatures and pressures and recombine into NOx compounds.

Zeldovich Mechanism

The sequence of the chemical reactions involved in the formation of thermal NOx is known as the Zeldovich mechanism.[2] As mentioned earlier, higher combustion temperatures create higher amounts of NOx compounds. The Zeldovich mechanism shows that the formation of thermal NOx is an exponential function of the flame temperature. It also shows that the NOx generated is dependent on the residence time (higher residence times tend to increase NOx). Therefore, the amount of NOx produced is highly dependent on the temperature and the time the reacting gases are at that temperature.

Gaseous fuels that contain higher molecular weight compounds (i.e. ethane, propane, and butane) will tend to burn hotter and therefore produce more NOx. On the other hand, gaseous fuels that contain higher amounts of inert gases, such as carbon dioxide, will produce less NOx because the inert gas will tend to absorb some of the heat from combustion. Flame temperatures will be somewhat lower, so less NOx is produced.

Below is listed the sequence of chemical reactions that form NOx under lean air/ fuel mixtures (with an excess of oxygen) according to the Zeldovich mechanism:[3]

#1 $O_2 \rightleftharpoons 2O$
#2 $N_2 \rightleftharpoons 2N$
#3 $N + O \rightleftharpoons \mathbf{NO}$
#4 $N + O_2 \rightleftharpoons \mathbf{NO} + O$
#5 $O + N_2 \rightleftharpoons \mathbf{NO} + N$

Under fuel rich conditions (with excessive fuel and a deficit of oxygen) additional chemical reactions occur:

#6 $N + OH \rightleftharpoons NO + H$
#7 $N2 + CH \rightleftharpoons HCN + N$
#8 $N + OH \rightleftharpoons H + NO$

In an actual operating engine, all of the above chemical reactions may occur because of imperfect mixing or because of the design of the engine. At any moment in time some parts of a combustion chamber may be lean while others may be rich.

301.1.2 Fuel Bound Nitrogen

Fuel NOx

The second NOx formation mechanism during combustion processes is due to the nitrogen content of the fuel. When a fuel is burned, any nitrogen in the fuel can react with atmospheric oxygen, forming NOx compounds. The nitrogen in the fuel is called **fuel bound nitrogen (FBN)** and it is chemically bound in the fuel. Sometimes fuel bound nitrogen is called "organic NOx" or "fuel NOx." A higher portion of NOx compounds is created by thermal NOx than fuel bound nitrogen.

Most types of natural gas and light petroleum distillate have little or no fuel bound nitrogen.[4] Lower quality, heavier petroleum distillates, process gases, sewage gases, and low Btu (British Thermal Unit, energy units usually associated with heat) coal gases (from gasifiers and hot gas cleanup) contain more fuel bound nitrogen. Coal may be heated in an oxygen deficient atmosphere to form combustible gases such as coke-oven gas or producer gas, which can be used as a fuel source. Compounds in fuels that contain nitrogen tend to reside in asphalt or heavy resin fractions in the fuel that managed to slip through refining processes. Nitrogen resides in pyridine-like (C_5H_5N) structures in petroleum fuels and coal.

The nitrogen content of most U.S. coals is between 0.5 to 2 %, for residual oils the nitrogen content is between 0.1 and 0.5 %, and most light distillate oils have a nitrogen content under 0.015%.[5] Today, more petroleum fuels come from poorer quality crude oils which have higher amounts of fuel bound nitrogen above 0.015%. Some low Btu synthetic fuels contain fuel bound nitrogen in the form of ammonia (NH_3).

Although the amount of NOx emissions increases with higher amounts of fuel bound nitrogen, the percentage of fuel bound nitrogen converted to NOx compounds decreases with increasing nitrogen content. For example, a fuel with 0.01% nitrogen may have 100% of the fuel bound nitrogen converted to NOx emissions, but a fuel with 1% nitrogen may have only 40% of the nitrogen converted to NOx. The fuel with 1% nitrogen would still have more NOx emissions than the fuel with 0.01% nitrogen.[6]

Prompt NOx

The third and less prominent NOx formation mechanism is from intermediate hydrocarbons present in the flames during the combustion process oxidizing to form NOx compounds. NOx from this mechanism is called "prompt NOx." Prompt NOx is a more important consideration for gas turbines, boilers and other combustion processes running to attain ultra-low emission levels. Below are chemical reactions involved in the formation of prompt NOx:

#1 $CH + N_2 \rightleftharpoons HCN + N$
#2 $CH2 + N_2 \rightleftharpoons HCN + NH$
#3 $HCN, N, NH + Ox \rightleftharpoons NO + \ldots$

301.1.3 NOx Effects on Health and the Environment

Nitrogen Dioxide

Ozone

The nitrogen dioxide (NO_2) is the pollutant form of NOx that is of primary concern. Nitrogen dioxide is a gas at ambient conditions and has a brownish color. The brownish haze seen over large cities is partially due to nitrogen dioxide. Most of the combustion emissions of NOx are in the form of nitric oxide (NO), but nitric oxide can react with ozone, which is photochemically produced from the energy of sunlight, to form nitrogen dioxide. NOx also contributes to photochemical reactions that create ozone (O_3), historically California's worst pollution problem.

NO_2 Air Quality Standards

Nitrogen dioxide is a reactive chemical and it is immediately dangerous to life and health (IDLH) at 50 ppm (parts per million, by volume). At relatively high concentrations it causes coughing, chest pain, and eye irritation. The State ambient air quality standard for nitrogen dioxide is 0.25 ppm for one hour. The federal standard is an annual average of 0.053 ppm.

Nitrogen dioxide damages the cells lining the respiratory tract and increases a person's susceptibility to respiratory infection. It also constricts the airways of asthmatics. Studies show that mice injected with cancer cells develop more tumors when exposed to nitrogen dioxide. Other studies with animals show that NO_2 adversely affects the kidneys, liver, spleen, red blood cells and immune system cells.

Acid Rain

NOx compounds also contribute to the formation of acid rain and when emitted high in the atmosphere may contribute to the depletion of the ozone layer. In the eastern U.S., 1/3 of the acid rain during a full year and 1/2 the acid rain in the winter is from NOx emissions.[7] Nitrogen oxides contribute to the nitrification of rain which can lead to an "overfertilizing" effect on the soil. This excessive fertilizing can make foliage more vulnerable to damage from cold weather, insects, and disease. NOx compounds also have a heat-trapping tendency and therefore contribute to global warming.

301.2 CARBON MONOXIDE EMISSIONS

Incomplete Combustion

Carbon Monoxide (CO) is emitted from reciprocating engines and other combustion devices due to incomplete combustion. Incomplete combustion can occur when there is too much fuel or not enough air in a combustion process. Incomplete combustion can also occur from insufficient fuel and air mixing, and excessively low combustion temperatures. Smoke can be a sign of incomplete combustion. Emissions of blue smoke are often due to burning lubricating oil, but black smoke may be due to the fuel burning. Carbon monoxide (CO) forms instead of carbon dioxide (CO_2) in incomplete combustion.

Smoke

As with the emissions of NOx compounds, carbon monoxide emissions are a function of temperature. Carbon monoxide emissions decrease with increasing temperatures. Therefore, there is a conflict in terms of temperature for carbon monoxide and NOx emissions. High temperatures will produce more NOx and less carbon monoxide, but lower temperatures will produce less NOx and more carbon monoxide.

301.2.1 Carbon Monoxide Health Effects

When drawn into the lungs, carbon monoxide binds tightly to hemoglobin, an oxygen carrying protein in the blood. Carbon monoxide binds tighter to hemoglobin than oxygen; therefore, oxygen is unable to bind to the hemoglobin, less oxygen enters the blood and less oxygen can reach the cells of the body. Every cell in the human body requires oxygen to stay alive.

Exposure to carbon monoxide can cause headaches, fatigue, and slowed reflexes. Higher concentrations can cause nausea, confusion and hallucinations. Carbon monoxide is especially dangerous to people with coronary artery disease since their hearts receive limited supplies of oxygen.

Any carbon monoxide compounds that manage to reach the upper atmosphere can destroy upper atmospheric ozone. When the carbon monoxide comes in contact with the ozone the two react to form oxygen and carbon dioxide. The ozone layer high in the atmosphere protects the earth from harmful ultraviolet rays from the sun.

CO Air Quality Standards

Carbon monoxide is immediately dangerous to life and health at 1500 ppm. The State ambient air quality standard for carbon monoxide is 9.0 ppm for 8 hours or 20 ppm for one hour. The federal ambient air quality standard is 9.0 ppm for 8 hours and 35 ppm for 1 hour. California also has a separate standard for carbon monoxide in the Lake Tahoe air basin of 6 ppm for 8 hours. California has a stricter standard for carbon monoxide in the Lake Tahoe air basin because at the high elevation of the air basin, the air is thinner and there is less oxygen to breathe. Carbon monoxide health effects are worse there because of the decrease in available oxygen.

Carbon monoxide is a pollutant that is directly emitted into the atmosphere, and it is not created photochemically as is NOx, but problems with carbon monoxide tend to be worse in the winter months. Photochemical pollutants such as ozone and NOx tend to be worse in the summer months when there is more sunshine. Over 18,000 tons per day of carbon monoxide are released into California's atmosphere, and 90% of the emissions are from motor vehicles.

301.3 SULFUR OXIDES (SOX)

Sulfur Dioxide

Sulfur oxides (SOx) are primarily sulfur dioxide (SO_2) but also include sulfur trioxide (SO_3). Sulfur dioxide comes from the combustion of fuels with sulfur in them. Sulfur compounds occur naturally in crude oils and most fuels are derived from petroleum. Unless the sulfur is removed, the sulfur in the fuel will also burn, forming sulfur dioxide and other sulfur compounds. Crude oils with high amounts of sulfur compounds are called "sour" crudes and crude oils with low amounts of sulfur are called "sweet" crudes. Sulfur burning in a fuel contributes to its energy output, but sulfur in a fuel is undesirable because it can cause corrosion of combustion equipment and because of the SOx emissions. Sulfur compounds can also be found in natural gas in the form of hydrogen sulfide (H_2S). Natural gas can be processed to remove sulfur compounds after it is recovered from a well. Sulfur compounds are also usually present in solid fossil fuels such as coal.

Hydrogen Sulfide

301.3.1 Sulfur Dioxide Health and Environmental Effects

Inhalation of sulfur dioxide can cause shortness of breath in people with asthma. It also adversely affects people with emphysema and chronic bronchitis. Higher levels of sulfur dioxide can cause healthy people to experience sore throats, coughing and breathing difficulties. The effects of sulfur dioxide are made worse by particulate matter and/or moisture. This is called a synergistic effect. Sulfur oxide emissions also contribute to acid rain.

SO_2 Air Quality Standards

The State ambient air quality standards for sulfur dioxide are 0.05 ppm over 24 hours and 0.25 ppm over 1 hour. The federal (primary) ambient air quality standards are an annual average of 80 $\mu g/m^3$ (0.03 ppm) and 365 $\mu g/m^3$ (0.14 ppm) over 24 hours. The federal standards also have a secondary standard of 1300 $\mu g/m^3$ (0.5 ppm) over 3 hours. Primary federal standards are set at levels to protect public health and secondary standards are set at levels to protect public welfare.

301.4 HYDROCARBON EMISSIONS

Volatile Organic Compounds

Ozone

Hydrocarbons are compounds made of carbon and hydrogen atoms, and fuels are mostly made up of different hydrocarbons. Many hydrocarbons are also volatile organic compounds (VOCs). VOCs are organic (carbon-containing) compounds that evaporate at a high rate at a low temperature. Hydrocarbon emissions from engines are a concern because volatile hydrocarbons can contribute to the formation of ozone (O_3), and ozone has been California's worst air pollution problem. Ozone is a photochemical pollutant; it is formed by chemical reactions from the energy of sunlight, hydrocarbons, and nitrogen oxides in the atmosphere.

Fuel Storage

Potential sources of hydrocarbon emissions from reciprocating engines are the fuel storage and transfer areas, and unburned hydrocarbons in the exhaust. Petroleum distillate fuels (e.g. gasoline) are sources of ozone precursors. Almost any petroleum distillate fuel can be used in a reciprocating engine. Emissions of unburned hydrocarbons from properly operating reciprocating engines are relatively low, especially for engines burning natural gas.

Engine Misfire

Engine misfire and deposits from fuel or oil are sources of hydrocarbon emissions. Engine misfire may be caused by a partial burn of the air/fuel mixture in a cylinder or a total absence of combustion. This results in part or all of the air and fuel mixture being exhausted into the atmosphere. Engines tend to have more misfire problems with leaner air/fuel ratios approaching the lean flammability limit. As an engine ages, deposits in the cylinder increase, so hydrocarbon emissions may increase. Fuel additives can be used to reduce the formation of deposits. When deposits form, pores within the deposits may not permit the flame to burn fuel within passages of the deposits. During the expansion stroke residual gases within the pores may exit the cylinder and become hydrocarbon emissions. The characteristics of the air/fuel ratio and the size of the pores in the deposits are factors that determine how well the flame will be able to propagate inside the pores to burn fuel.

Layers of oil in an engine can also trap fuel which can become hydrocarbon emissions. Hydrocarbons trapped in the oil may not be oxidized and may be released during the expansion stroke. One study showed that when oil was added to the cylinder of an engine a proportional increase in unburned hydrocarbons occurred. It was verified that the source of the hydrocarbons was the fuel and not the oxidation of the oil. Tests with propane, which is a fuel that was not soluble with the oil, indicated no increase in hydrocarbon emissions when oil was added. Therefore, the solubility of the fuel and the oil and the amount of oil in the cylinder can affect hydrocarbon emissions.[8]

The small area between the piston and the cylinder wall above the rings, also called the clearance volume, may be a source of hydrocarbon emissions. It is a small area where flame may not be able to propagate well. Quenching of the flame on the cylinder walls is also thought to be a source of hydrocarbons. Research has showed that the flame in a cylinder may be extinguished a small distance from the cylinder walls. Some researchers doubt oil layers are a source of emissions, but believe quenching is the larger source.

Any of the hydrocarbons emitted from a cylinder may be oxidized before they reach the atmosphere. Many hydrocarbons may be oxidized in the exhaust ports after exiting the cylinders. Some emission control systems oxidize hydrocarbons in the exhaust manifold with air.

Hydrocarbon emissions are a larger problem with spark ignition engines, but the main sources of hydrocarbon emissions in diesel engines are from fuel trapped in the injectors after injection, areas around the spray that are too lean to burn and fuel trapped along the walls of the combustion chamber by crevices, deposits, or oil due to impingement by the injector spray.[9]

Aldehydes

Partially oxidized hydrocarbon compounds can form aldehydes (-CHO). The combustion of liquid fuels (aldehyde emissions from gaseous fuels are very low relative to liquid fuels) and lube oil in an engine can form aldehydes. They may come from quenching of the flame on the walls of the cylinder and in other low temperature areas in an engine. Aldehydes can also form from photochemical reactions involving hydrocarbons and oxygen. Some of the unbalanced chemical reactions involved include:[10]

O_3 + NMHC - CHO + CO_2
O + NMHC - CHO + CO_2
where: NMHC = non-methane hydrocarbon

Aldehydes contribute to eye irritation and can polymerize and form visibility-reducing aerosols.

Not only do emissions of volatile organic compounds in the atmosphere cause the formation of smog, but many VOCs are directly toxic or hazardous to a person's health. Although combustion sources, such reciprocating engines, emit unburned hydrocarbons and other toxic compounds, most of the main sources of direct exposure to VOCs come from the handling of fuels, solvents, coatings, and other sources where individuals are directly exposed to evaporative emissions.

Exposure to VOCs can have specific acute (short term) and chronic (long term) effects. Acute health effects of VOCs include: irritation and burning of the eyes, skin, nose and throat; dizziness, headache, and nausea; and even respiratory arrest. Chronic effects caused by VOCs entering the blood stream through the lungs or skin include: permanent vision damage, liver disease, kidney disease, contact dermatitis, and nervous system disorders. Workers at facilities using VOC products (i.e. paints, solvents, coatings etc.) should have a permissible exposure limit (PEL) to VOCs, which is the amount of a compound that workers can be safely exposed to in an eight hour day.

301.4.1 Ozone Health Effects

Ozone is a very reactive chemical. When it forms in high concentrations in the lower atmosphere it damages plants, the lungs of people and the surfaces of cars and buildings.

Ozone attacks the leaves of plants and causes them to yellow, develop dead areas, and die. Ozone makes crops more susceptible to disease and insect attack and reduces their yield. Ozone is a major component of smog and smog is estimated to cost California between 150 million to 1 billion dollars a year in crop damage.

Research sponsored by the Air Resources Board has shown that exposure to ozone damages the alveoli, the air sacs in the lungs where the exchange of oxygen and carbon dioxide between the air and blood takes place. This injury results in lung inflammation and changes in breathing. Repeated injury is thought to lead to permanent lung damage. Exposure to ozone can also cause burning sensations in the chest, throat, and eyes.

Ozone Air Quality Standards

The State ambient air quality standard for ozone is 0.09 ppm over one hour, and the federal standard is 0.12 ppm over one hour.

301.5 PARTICULATE MATTER EMISSIONS

Particulate matter is small, liquid or solid particles of material that can easily become airborne. The burning of fossil fuels and wood, photochemical reactions and agricultural operations are all man-made sources of particulate matter pollution. Most of the particles that get into the atmosphere are from natural sources, but human activities are the main source of particulate matter in urban areas, where the most people are exposed to it. Man-made sources of particulate are of greatest concern, since they are a greater health risk and more people are exposed to man-made particulates. People in rural areas can also be exposed to particulates from farming activities, woodburning, and transport from urban areas. Poor weather conditions can also worsen exposure to particulates.

PM_{10} Air Quality Standards

The greatest concern is for the very small particles that are less than 10.0 microns or micrometers (10.0×10^{-6} meters) in diameter, since these particles can easily bypass the lung's natural filtering system. Ten microns is about one fifth the diameter of a thin human hair. Particles of this size are also called "PM10." The weight-based State ambient air quality standards for PM10 are 30$\mu g/m^3$ (micrograms per cubic meter of air) averaged over a year and 50 $\mu g/m^3$ averaged over 24 hours. The federal ambient air quality standards are 150 $\mu g/m^3$ for 24 hours and an annual arithmetic mean of 50 $\mu g/m^3$.

The major sources of natural particulate matter include forest fires, soil debris, volcanoes and ocean salt spray. Some forest and brush fires are human-caused. All types of burning are sources of particulate matter. Fugitive dust is a type of particulate matter that originates primarily from human activities disturbing the soil. Unpaved roads, farming, construction, off-road vehicles, and mining are some of the major causes of fugitive dust.

Besides being directly emitted into the atmosphere, particulate matter can be created in the atmosphere by chemical reactions. Sulfur dioxide emissions and nitrogen oxide emissions released into the atmosphere can later develop into sulfate and nitrate particles respectively through chemical reactions. Any fuel used in a reciprocating engine containing sulfur compounds will emit sulfur oxides. Reciprocating engines can also produce large amounts of nitrogen oxides.

The major categories of man-made sources of particulate matter are stationary source fuel combustion, industrial processes, and solid waste disposal. Combustion from stationary sources is responsible for 35 to 50% of the total particulate matter from man-made sources.[11] Stationary reciprocating engines are sources of fuel combustion, but particulate emissions are usually a small problem, especially for spark ignition engines and compared to NOx emissions. Many engines often burn natural gas, which has little or no potential for particulate emissions. Heavier fuels such as distillate oil have a much higher potential to release particulates.

Oil Burning

Most of the particulate matter emissions from an engine result from incomplete combustion and burning of the lubricating oil. Lubricating oil contributes 50 to 280 times as much material to particulate matter than fuel.[12] A small amount of oil consumption can have a large effect on emissions. Excessive burning of the lubricating oil forms smoke with a blue color, but under some conditions unburned fuel can also form blue smoke.

Diesel Fuel

Diesel fuel has higher particulate emissions. An important parameter for the fuels in terms of particulate emissions is the aromatic and sulfur content. Aromatics are hydrocarbons with a ring structure that tend to have a sweet smell. Fuels with a higher aromatic content and sulfur content will have more particulate emissions. Additives such as alkaline earths, barium, and calcium can be added to diesel fuel can reduce the opacity of the smoke from the exhaust.

As liquid fuel is injected into a combustion process, the fuel is atomized into small droplets. When the liquid droplets enter the combustion chamber the volatile substances are vaporized and then oxidized, releasing energy. After volatile materials are vaporized and driven from the liquid state, ash and char still remain. Ash is incombustible material and char is slow burning organic compounds. Most of the char may still burn during a combustion process, but ash and any remaining char can become particulate emissions when they exit the exhaust pipe or stack.

Soot

Solid material collected from a diesel engine may be classified as soot (solid carbon material) and organic fractions consisting of hydrocarbons and their partially oxidized products. Soot is believed to come primarily from parts of the fuel spray that are not leaned out until combustion gases have cooled considerably from expansion. Organic fractions result from processes that create hydrocarbon emissions (i.e. quenching of the flame at the cylinder walls, deposits, etc.). Studies have shown that 25% to 75% of organic fraction particulate may be from the lubricating oil.[13]

Homogeneous, Heterogeneous Nucleation

Particulates can also be formed in a combustion process from homogeneous nucleation and heterogeneous nucleation. During homogeneous nucleation, new particles are created from vapor phase materials cooling and condensing, forming particulates. When heterogeneous nucleation occurs, material collects on the surfaces of existing particles. Homogeneous and heterogeneous nucleation occur when substances in the exhaust cool below their dewpoint and condense. The gaseous materials in the exhaust that can nucleate and form particulates include organic compounds, metals, and metal compounds. Metal compounds such as mercury, lead, cadmium, and arsenic can nucleate, and most of these compounds can be found in solid fuels and liquid fuels. Many of these compounds are toxic; therefore particulates can become carriers of toxic compounds.

Metal compounds tend to nucleate first after combustion since they have higher dewpoints. Particles created by homogeneous and heterogenous nucleation are very small, ranging from 0.05 to 1.0 microns.

301.5.1 Particulate Matter Health Effects

Short term exposure to particulate matter can lead to coughing and throat irritation. Inhaled particles can irritate the respiratory tract, constrict airways and interfere with the mucous lining of the airways. Longer term exposures can lead to increased chances of developing bronchial disease, a disease of the lungs. Particulates can be composed of metals and toxic compounds or they may carry carcinogens such as dioxins or benzene. These particles can get deep into the lungs and increase the probability of cancer. The EPA now also believes that inhaling particulate matter contributes to up to 60,000 deaths a year in people with preexisting respiratory and heart ailments.

Particulate matter is a form of pollution that reduces visibility. Some forms of particulate matter can also damage the surfaces of buildings, the finishes of cars, and other objects.

302 FACTORS AFFECTING RECIPROCATING ENGINE EMISSIONS

The main factors that affect emissions of NOx, hydrocarbons and carbon monoxide from engines include atmospheric conditions, air/fuel ratio, charging method, ignition timing, combustion cycle, load and speed, valve and combustion chamber design, and the fuel.

302.1 ATMOSPHERIC CONDITIONS

NOx Emissions

The atmospheric conditions that affect NOx emissions are humidity, temperature and pressure. Water vapor in atmospheric air tends to decrease the peak temperatures in the cylinders of an engine. High moisture conditions have been found to decrease NOx emissions up to 25%.[14] Energy is required to heat the water vapor in atmospheric air and lower temperatures in the combustion chamber create less NOx.

Many of the changes in NOx emissions from temperature and pressure are due to changes in the air/fuel ratio from changes in the air density. Different engines are designed to operate at different air/fuel ratios, so changes in atmospheric conditions make engines respond differently. This makes it difficult to quantify changes in emissions from atmospheric conditions. On the other hand, tests from automotive manufacturers indicate that the ambient temperature may have up to a 25% change in NOx and that changes in ambient pressure may have up to a 40% change in NOx emissions.[15]

HC and CO Emissions

In addition, atmospheric conditions can affect hydrocarbon and carbon monoxide emissions. For engines operating near stoichiometric, increases in the intake manifold air temperature may increase hydrocarbon and carbon monoxide emissions. Near stoichiometric, decreases in ambient pressure increase hydrocarbon and carbon monoxide emissions.

302.2 AIR/FUEL RATIO

Figure 302.1 illustrates how emissions vary with air/fuel ratio. Air/fuel ratios that are below stoichiometric are rich mixtures of air and fuel, because there is more fuel compared to air relative to that required for stoichiometric combustion. Air/fuel ratios are lean when there is more air compared to fuel relative to stoichiometric requirements. The stoichiometric ratio of air to fuel by weight is approximately 14.7 to 1.0 for gasoline engines, and about 16.0 to 1.0 for natural gas engines.

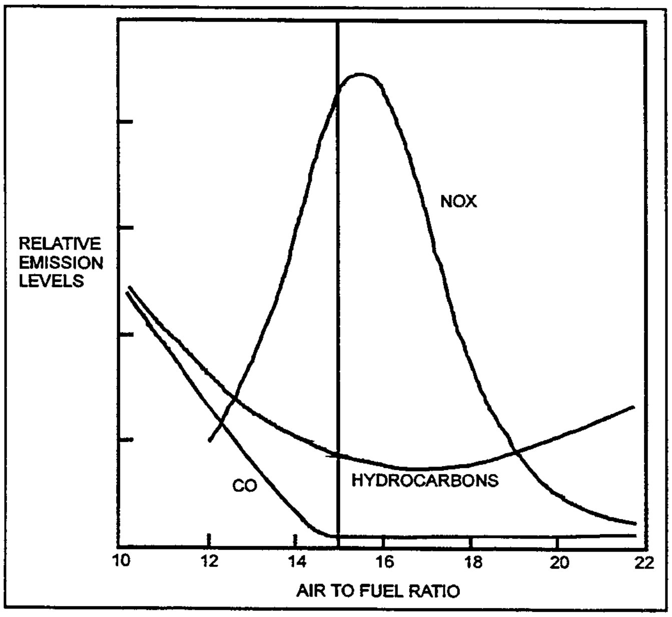

Figure 302.1 Effect of Air/Fuel Ratio on NOx, CO and Hydrocarbons

Lean Air/Fuel Ratios

Maximum NOx emissions occur just above stoichiometric at slightly lean air/fuel ratios. Higher combustion temperatures create more NOx and this point is also where maximum temperatures occur. Unfortunately, combustion performance peaks in this area of slightly lean air/fuel ratios and high temperatures. As the air/fuel ratio decreases, NOx emissions decrease due to the absence of excess oxygen and lower temperatures. Above stoichiometric, NOx emissions increase slightly to a maximum value and then decrease. As the air/fuel mixture gets leaner above the point of peak NOx emissions, the increase in excess air tends to behave as a heat sink and cools the combustion. The lower temperatures produce less NOx.

Rich Air/Fuel Ratios

Under rich conditions the carbon monoxide emissions increase substantially. Because there is an abundance of fuel but a lack of oxygen, fuel compounds may not be completely oxidized to carbon dioxide (CO_2), so carbon monoxide (CO) forms. Black smoke, an indication of incomplete combustion, can also form under very rich conditions. A key to reducing carbon monoxide emissions from engines is minimizing the time that the engine runs rich. Under leaner air/fuel ratios carbon monoxide problems are reduced. Since diesel engines are run lean, they generally do not have excessive carbon monoxide emission problems. Hydrocarbon emissions also increase under increasingly rich conditions since there is not enough oxygen to oxidize the fuel completely. Hydrocarbons may not be able to find oxygen molecules to react with during the short period of combustion since the relative amount of oxygen is lower. Under lean conditions hydrocarbon emissions increase from the cooling effect of the excess air. The cooler temperatures inhibit combustion.

302.3 CHARGING METHOD

The three main types of charging methods include turbocharging and supercharging, natural aspiration, and blower scavenging. Engines that are turbocharged and fuel injected can be equipped to provide precise delivery of fuel and air to each cylinder. Turbocharging or supercharging may not necessarily improve the precision of air delivery to the cylinders, but fuel injection can improve fuel delivery precision. In order to reduce emissions, turbocharged, fuel injected engines can operate with very lean air/fuel ratios approaching the lean flammability limit. Naturally aspirated engines may operate more imprecisely, especially if equipped with the float type carburetor. The lack of control could result in misfiring or incomplete combustion at some cylinders if the engine's air/fuel ratio is set very lean. Blower scavenging can produce higher emissions since part of the air/fuel charge may be emitted with the scavenged exhaust gases.

Fuels with broader ranges of flammability limit can be leaned further than fuels with narrower limits. Engines using natural gas, for example, can be leaned further than engines using gasoline.

302.4 IGNITION TIMING

In a spark ignition engine combustion can be retarded or delayed by making the spark plug fire at a later time during the cycle. In a compression ignition engine, combustion can be delayed by injecting the fuel at a later time. In both engines, delaying ignition makes combustion occur at a later time when the piston has moved further down the cylinder. The combustion chamber then has a larger volume, reducing the pressure and possibly the peak temperature of combustion. For most engines the result is lower NOx emissions. Emissions of carbon monoxide and hydrocarbons are usually not heavily affected unless misfiring occurs. This usually only happens when the ignition retarding is excessive.

Some problems with ignition retarding are a reduction in efficiency and smoke emissions. When the ignition is delayed the maximum pressure in the cylinder is lowered. With lower pressures there is less force to drive the pistons and the horsepower output is reduced. Fuel consumption must be increased to keep up with power demand, so the efficiency is lowered.

Moderate or high amounts of timing retard in diesel engines can produce excessive amounts of smoke. More soot can get into the lubrication oil and this requires more frequent oil changes.

302.5 COMBUSTION CYCLE

Whether an engine operates on a two or four stroke cycle affects pollutant emissions. In non-injected or carbureted two cycle engines, scavenging air purges the cylinder of exhaust gases, but this may also sweep out part of the fuel charge for the next cycle. This will result in increased hydrocarbon emissions.

On the other hand, any remaining exhaust gases in the cylinder of a two cycle engine will tend to cool combustion. The exhaust gas behaves as an inert gas that absorbs some of the heat of combustion. The lower temperatures in the cylinder produce less NOx.

302.6 LOAD AND SPEED

The effect of load and speed on emissions varies between different engines. One manufacture states that on a mass basis (lbm/hr) NOx emissions increase with increasing power output, but on a power specific basis (g/Bhp-hr, or grams per brake horsepower-hour) NOx emissions decrease with increasing power output.[16] A second manufacturer states that for their spark ignition engines, NOx emissions decrease with increases in load if the engine speed is made to decrease with decreasing load. If the engine speed is constant, the NOx emissions on a brake specific power (g/Bhp-hr) basis decrease with decreasing load.

In general, for diesel engines brake specific NOx emissions (g/Bhp-hr) decrease with increasing load at a constant speed. This may be partially due to increases in efficiency at higher power outputs. Some turbocharged diesel engines show an opposite effect. Since diesels are lean-burn engines and vary air/fuel ratios depending on the load, increasing the load causes the air/fuel ratio to decrease (from very lean to less lean, closer to stoichiometric) which should increase NOx emissions. Carbon monoxide emissions first decrease with increasing load, due to increase in the temperature of combustion, and then increase as the maximum load is approached.

302.7 VALVE AND COMBUSTION CHAMBER DESIGN

Although the effects on emissions from the valve and combustion chamber design cannot be quantified because each engine is different, the design has a significant effect on emissions. Changing a given aspect of the design of the valves or combustion chamber may have a positive effect in some engines, but not in others.

Air/Fuel Mixing

On the other hand, some general design variables that can help reduce emissions include improving the mixing in the combustion chamber, improving fuel atomization, optimizing fuel injection locations and reducing the compression ratio.[17] Improving the mixing of fuel and air in the engine makes the combustion more complete and can reduce emissions of carbon monoxide and hydrocarbons. This may be accomplished by designing the combustion chamber so that the air and fuel will have a swirling motion in the cylinder. Turbulence, one of the three T's of combustion, is increased and combustion is improved. In a similar manner, good fuel atomization provides good mixing of the fuel and air so that oxygen from the air and hydrocarbons from the fuel can come in contact and react during the short period of combustion. For different engines the location of the injectors can have an effect on emissions. Reducing the compression ratio can be a method to reduce emissions, especially in older engines. This reduces the pressure and temperature in the cylinder during combustion, so that NOx emissions can be reduced. A negative attribute of reducing the compression ratio is that it causes a reduction in power output and efficiency.

The temperature of the cooling system and engine deposits can affect NOx emissions. Higher temperatures from reduced cooling can create more NOx. Deposits in the combustion chamber will also tend to increase temperatures and NOx emissions.

302.8 FUEL TYPE

As discussed earlier, fuels derived from residual or poorer quality crude oils have higher amounts of fuel bound nitrogen and will have higher NOx emissions. Gaseous fuels consisting of waste gases or coal gas will have higher NOx emissions than natural gas because of the higher nitrogen content.

Figure 302.2 illustrates the emissions of different gaseous fuels from NOx and CO emissions. Landfill and digester gases are alternative fuels and have lower NOx emissions because they have a relatively low Btu content and a lower flame temperature. Since landfill and digester gases burn at lower temperatures, less NOx is produced. The composition of different landfill and digester gases varies, but landfill gas contains approximately 45% carbon dioxide and digester gas contains approximately 35% carbon dioxide.[18] Methane primarily makes up the rest of the gases. The gases can also be saturated with water vapor. Carbon dioxide and water absorb some of the heat of combustion, resulting in lower combustion temperatures.

Excess Air Ratio

The excess air ratio is the actual air/fuel ratio divided by the stoichiometric air/ fuel ratio:

Excess air ratio = [Air/Fuel (actual)]/[Air/Fuel (stoichiometric)]

The effect of reduced emissions is greatest from excess air ratios near stoichiometric (1.0) to approximately 1.4. This is also within the range of rich-

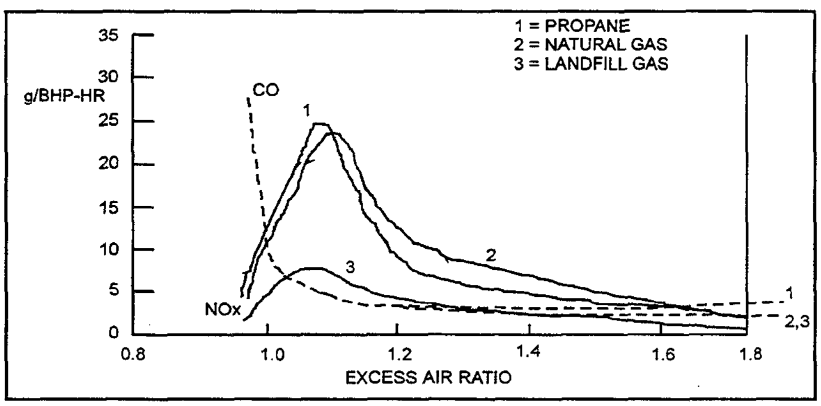

Figure 302.2 NOx, CO Emissions from Gaseous Fuels

burn and lean-burn spark ignition engines. Figure 302.2 also shows NOx emissions versus excess air ratio. Emissions from the use of landfill gas are reduced. Hydrocarbon emissions from landfill gas and digester gas are lower than the emissions from natural gas.

303 QUANTITY OF CALIFORNIA RECIPROCATING ENGINE EMISSIONS

This section contains tables created from 1993 emission inventory data showing estimates of emissions from stationary reciprocating engines. The tables appear on pages 22 through 33. The emissions are categorized by air basin. The air basins contain the following counties:

1. Great Basin Valleys: Alpine, Inyo, Mono
2. Lake County
3. Lake Tahoe: El Dorado, Placer
4. Mountain Counties: Amador, Calaveras, El Dorado, Mariposa, Nevada, Placer, Plumas, Sierra, Tuolumne
5. North Coast: Del Norte, Humboldt, Mendocino, Sonoma, Trinity
6. North Central Coast: Monterey, San Benito, Santa Cruz
7. Northeast Plateau: Lassen, Modoc, Siskiyou
8. Sacramento Valley: Butte, Colusa, Glenn, Placer, Sacramento, Shasta, Solano, Sutter, Tehama, Yolo, Yuba
9. San Diego
10. San Francisco Bay Area: Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, Solano, Sonoma
11. San Joaquin Valley: Fresno, Kern, Kings, Madera, Merced, San Joaquin, Stanislaus, Tulare
12. South Central Coast: San Luis Obispo, Santa Barbara, Ventura
13. South Coast: Los Angeles, Orange, Riverside, San Bernardino
14. Southeast Desert: Imperial, Kern, Los Angeles, Riverside, San Bernardino

The types of pollutants in the tables are:

TOG (Total Organic Gas) - All the organic gas emissions from engines.
ROG (Reactive Organic Gas) - All the organic gas emissions that are reactive. These compounds are ozone precursors. The reactive organic gas emissions are included in the total organic gas emissions. From the emissions in the tables, it is evident that total organic gas emissions are greater than the reactive organic emissions since some of the emissions are not reactive.

CO - Carbon monoxide.
NOx - Nitrogen oxides.
SOx - Sulfur oxides.
PM - Particulate matter.

The emissions tables are: stationary engines, area sources, manufacturing and industrial natural gas fuel (Table 303.1); stationary engines, area sources, manufacturing and industrial diesel fuel (Table 303.2); stationary engines, area sources, manufacturing and industrial other fuels (Table 303.3); stationary engines, area sources, petroleum production liquid fuels (Table 303.4); stationary engines, area sources, petroleum production gaseous fuels (Table 303.5); stationary engines, area sources, utility equipment, residential (Table 303.6); stationary engines, area sources, utility equipment, commercial (Table 303.7); stationary engines, point sources, electric generation (Table 303.8); stationary engines, point sources, industrial (Tables 303.9a, 303.9b, 303.9c); stationary engines, point sources, engine testing (Table 303.10); and stationary engines, point sources, commercial-institutional (Tables 303.11a, 303.11b).

Table 303.12 shows emissions factors from several reciprocating engine manufacturers.[19] The emissions are averaged from engines with similar power ratings and the second column shows the number of engines used for the averaging. Emissions can be calculated by multiplying the emission factors by the power output at which the engine is operating. For example, if the emission factor from natural gas is 4.0 lbm NOx/MMBtu and the output power is 10 MMBtu/hr, the emissions would be (4.0 lb NOx/MMBtu)(10 MMBtu/hr) = 40 lbm NOx/hr.

For rich-burn engines the average NOx emission factors range from 3.54 to 4.87 lbm/MMBtu or 13.1 to 16.4 g/hp-hr; for lean-burn engines they range from 1.99 to 5.46 lbm/MMBtu or 7.9 to 18.6 g/hp-hr. For diesel engines they range from 3.66 to 4.26 lbm/MMBtu or 11.2 to 13.0 g/hp-hr, and for Dual fuel engines the average emission factors range from 1.75 to 3.26 lbm/ MMBtu or 4.9 to 10.7 g/ hp-hr. The 1.99 lbm/MMBtu emissions from the smallest lean-burn engine category is somewhat lower than emissions from other lean-burn engines due to low emissions reported by one manufacturer. Dual fuel engines have the lowest emissions, ranging from 1.75 to 3.26 lbm/MMBtu.

300 EMISSION CONTROL

Table 303.1 Stationary Reciprocating Engines Emissions (Tons/year)- Area Sources, Manufacturing & Industrial, Natural Gas Fuel						
Air Basin	TOG	ROG	CO	NOx	SOx	PM
South Coast	5.72	1.17	1.81	13.67	0.00	0.06
S. Central Coast	0.36	0.07	0.32	0.30	0.00	0.02
San Diego	0.00	0.00	0.03	0.02	0.00	0.00
S.E. Desert	9.44	1.93	0.18	6.43	0.00	0.00
Bay Area	0.01	0.00	0.03	0.04	0.00	0.00
San Joaquin	0.00	0.00	0.15	2.76	0.00	0.00
Sacramento	0.10	0.02	0.10	0.01	0.00	0.00
TOTAL	15.63	3.19	2.61	23.33	0.01	0.08

Table 303.2 Stationary Reciprocating Engines Emissions (Tons/year)- Area Sources, Manufacturing & Industrial, Diesel Fuel						
Air Basin	TOG	ROG	CO	NOx	SOx	PM
Outer Cont. Shelf	0.01	0.01	0.01	0.04	0.00	0.00
South Coast	1.53	1.49	3.82	21.36	1.42	1.54
S. Central Coast	0.14	0.13	0.37	1.69	0.11	0.12
San Diego	0.62	0.61	0.61	2.45	0.14	0.15
S.E. Desert	0.06	0.05	0.17	0.78	0.05	0.05
Bay Area	0.01	0.01	0.02	0.10	0.01	0.01
San Joaquin	0.00	0.00	0.00	0.01	0.00	0.00
Sacramento	0.01	0.01	0.01	0.05	0.00	0.00
TOTAL	2.36	2.30	5.01	26.48	1.75	1.88

Table 303.3 Stationary Reciprocating Engines Emissions (Tons/year)- Area Sources, Manufacturing & Industrial, Other Fuels						
Air Basin	TOG	ROG	CO	NOx	SOx	PM
South Coast	0.47	0.35	1.14	0.77	0.02	0.03
S. Central Coast	0.00	0.00	0.02	0.00	0.00	0.00
S.E. Desert	0.03	0.02	0.20	0.03	0.00	0.00
Bay Area	0.00	0.00	0.01	0.05	0.00	0.00
San Joaquin	0.01	0.01	0.18	0.00	0.00	0.00
TOTAL	0.51	0.38	1.56	0.86	0.02	0.03

Table 303.4 Stationary Reciprocating Engines Emissions (Tons/year)- Area Sources, Petroleum Production, Liquid Fuels						
Air Basin	TOG	ROG	CO	NOx	SOx	PM
N. Central Coast	0.00	0.00	0.01	0.02	0.00	0.00
Outer Cont. Shelf	0.01	0.01	0.02	0.10	0.01	0.01
South Coast	0.00	0.00	0.02	0.02	0.00	0.00
San Joaquin	0.15	0.13	0.60	6.58	0.86	1.44
TOTAL	0.16	0.14	0.64	6.72	0.86	1.44

Table 303.5 Stationary Reciprocating Engines Emissions (Tons/year)- Area Sources, Petroleum Production, Gaseous Fuels						
Air Basin	TOG	ROG	CO	NOx	SOx	PM
Outer Cont. Shelf	0.01	0.00	0.03	0.07	0.00	0.00
South Coast	0.22	0.90	0.07	0.47	0.00	0.00
S. Central Coast	0.37	0.15	0.93	0.56	0.00	0.00
Bay Area	0.40	0.01	0.01	0.09	0.00	0.00
San Joaquin	7.31	2.90	5.20	16.54	0.00	0.03
Sacramento	0.20	0.08	0.06	0.49	0.00	0.00
TOTAL	8.15	3.23	6.30	18.22	0.00	0.04

303.1 RICH-BURN AND LEAN-BURN CLASSIFICATION

Besides spark ignition and compression ignition, all reciprocating engines can be classified as rich-burn or lean-burn engines. The class of an engine is determined by the air/fuel ratio at which it operates. The theoretical stoichiometric air/fuel ratio is the point where the amount of fuel relative to the amount of air for combustion in an ideal engine is exact, leaving no oxygen or unburned fuel in the exhaust. A rich-burn engine operates with an air/fuel mixture that is nearly stoichiometric or rich. District regulations define a rich-burn engine as one with less than 4% oxygen in the exhaust. A lean-burn engine operates with an air/fuel ratio that is lean (an air/fuel ratio above stoichiometric), where there is more oxygen than required to burn the available fuel.

Reference two from the EPA has a different definition that is based more on operation capability. It states that a rich-burn engine operates with an air/fuel mixture that is nearly stoichiometric or rich and can be **adjusted** to operate with

Table 303.6 Stationary Reciprocating Engines Emissions (Tons/year)- Area Sources, Utility Equipment, Residential

Air Basin	TOG	ROG	CO	NOx	SOx	PM
Great Basin	0.03	0.02	0.21	0.00	0.00	0.00
Lake County	0.04	0.04	0.36	0.00	0.00	0.00
Lake Tahoe	0.06	0.06	0.39	0.00	0.00	0.00
Mountain Counties	0.62	0.60	3.53	0.01	0.00	0.01
North Coast	0.62	0.60	2.82	0.01	0.00	0.01
N. Central Coast	0.35	0.34	3.09	0.01	0.00	0.01
N.E. Plateau	0.24	0.23	0.94	0.00	0.00	0.00
South Coast	6.20	6.00	55.33	0.26	0.01	0.12
S. Central Coast	0.71	0.69	6.35	0.03	0.00	0.01
San Diego	1.24	1.20	11.14	0.05	0.00	0.02
S.E. Desert	0.58	0.56	5.20	0.02	0.00	0.01
Bay Area	3.18	3.08	28.35	0.13	0.01	0.06
San Joaquin	1.64	1.58	14.26	0.07	0.00	0.03
Sacramento	1.38	1.34	11.40	0.05	0.00	0.03
TOTAL	16.89	16.34	143.36	0.65	0.03	0.32

Table 303.7 Stationary Reciprocating Engines Emissions (Tons/year)- Area Sources, Utility Equipment, Commercial

Air Basin	TOG	ROG	CO	NOx	SOx	PM
Great Basin	0.09	0.08	0.58	0.00	0.00	0.00
Lake County	0.17	0.17	1.07	0.00	0.00	0.00
Lake Tahoe	0.33	0.31	1.57	0.00	0.00	0.01
Mountain Counties	3.95	3.82	17.22	0.05	0.00	0.09
North Coast	4.96	4.80	19.32	0.05	0.01	0.12
N. Central Coast	1.02	0.98	7.83	0.03	0.00	0.02
N.E. Plateau	2.03	1.97	7.57	0.02	0.00	0.05
South Coast	16.91	16.36	133.67	0.56	0.04	0.32
S. Central Coast	1.95	1.88	15.38	0.06	0.00	0.04
San Diego	3.44	3.33	27.19	0.11	0.01	0.07
S.E. Desert	1.53	1.48	12.07	0.05	0.00	0.03
Bay Area	4.95	4.79	49.27	0.23	0.02	0.09
San Joaquin	4.94	4.78	36.31	0.15	0.01	0.10
Sacramento	4.90	4.74	31.82	0.12	0.01	0.10
TOTAL	51.15	49.49	360.87	1.44	0.10	1.03

Table 303.8 Stationary Reciprocating Engines Emissions - Point Sources, Electric Generation (Tons/Year)								
Air Basin	Fuel Type	TOG	ROG	CO	NOx	SOx	PM	PM10
Bay Area	dist. oil/diesel	15.00	11.00	42.10	197.50	14.0	13.2	12.90
	natural gas	247.70	18.30	188.10	202.30	8.40	5.1	5.10
	landfill gas	100.80	7.50	667.70	320.10	2.40	10.2	10.10
	jet fuel	0.00	0.00	0.10	0.00	0.00	0.00	0.00
	total	363.50	36.80	898.00	719.90	24.8	28.5	28.1
Great Basin	distillate oil/ diesel	0.00	0.00	3.30	14.70	1.00	1.0	1.00
Lake County		4.40	3.20	12.20	59.90	3.60	4.10	4.00
Mtn. County		4.30	3.20	19.40	81.00	10.6	7.10	6.90
N. Ctr. Coast	landfill gas	205.90	15.20	85.90	18.40	2.60	2.30	2.30
Sacramento	dist. oil/diesel	2.30	1.70	6.70	30.20	2.00	2.1	2.00
	natural gas	7.60	0.60	0.70	6.20	0.00	0.00	0.00
	process gas	101.50	7.50	36.20	32.30	3.40	2.50	2.50
	total	111.40	9.80	43.60	68.70	5.40	4.60	4.50
San Diego	dist. oil/diesel	1.80	1.30	5.10	23.90	0.50	1.7	1.70
	landfill gas	147.50	2.10	90.80	44.60	3.40	1.60	1.60
	total	149.30	3.50	95.90	68.50	3.90	3.30	3.20
San Joaquin	dist. oil/diesel	0.40	0.30	1.20	8.60	0.50	0.60	0.60
	natural gas	233.10	17.20	87.50	525.50	0.10	2.10	2.10
	process gas	1.50	0.10	9.20	36.80	0.20	1.30	1.30
	landfill gas	0.50	0.00	23.00	7.40	0.20	0.00	0.00
	total	235.50	17.70	120.90	578.30	1.00	4.00	4.00
South Central Coast	dist. oil/diesel	0.40	0.30	2.80	10.60	1.50	1.10	1.1
	natural gas	0.70	0.10	19.50	0.50	0.00	0.00	0.00
	total	1.10	0.30	22.30	11.10	1.50	1.10	1.10
S. E. Desert	dist. oil/diesel	3.10	2.30	8.00	73.80	3.10	3.50	3.40
Total	---	1302.3	142.30	1890.3	2583.2	96.8	105.	103.0

Table 303.9a Stationary Reciprocating Engines Emissions - Point Sources, Industrial (Tons/Year)								
Air Basin	Fuel Type	TOG	ROG	CO	NOx	SOx	PM	PM10
Bay Area	dist. oil/diesel	0.40	0.30	1.60	7.90	0.60	0.50	0.50
	natural gas	127.60	9.40	119.20	656.60	0.40	2.40	2.40
	natural gas/ cogeneration	402.90	29.80	1008.9	2414.5	6.70	149.	148.4
	large bore diesel	0.00	0.00	0.10	0.60	0.00	0.00	0.00
	total	530.90	39.60	1129.8	3079.6	7.70	152.	151.3
Great Basin	dist. oil/diesel	0.00	0.00	1.00	4.70	0.30	0.20	0.20
	large bore diesel	0.00	0.00	3.00	11.40	3.60	1.10	1.10
	total	0.00	0.00	4.00	16.10	3.90	1.30	1.30
Mountain Counties	distillate oil/ diesel	8.70	6.40	23.40	108.00	7.30	7.70	7.50
N. Central Coast	landfill gas	3.50	2.60	7.90	36.30	2.40	2.50	2.4
	natural gas	4.60	0.30	1.40	11.00	0.10	0.00	0.00
	large bore cogeneration /dual fuel	117.70	78.00	42.70	81.80	1.40	2.20	1.50
	total	119.80	80.90	52.00	129.10	3.90	4.70	4.00
Outer Cont. Shelf	distillate oil/ diesel	0.80	0.60	2.20	10.10	0.30	0.70	0.70
	large bore diesel	0.10	0.10	0.30	1.20	0.10	0.10	0.10
	total	0.90	0.70	2.50	11.30	0.40	0.80	0.80
Sacramento	distillate oil/ diesel	1.60	1.20	4.00	18.50	1.20	1.40	1.40
	natural gas	425.20	31.50	136.00	1052.1	0.00	0.20	0.20
	natural gas/ cogeneration	3.00	0.20	114.80	26.10	0.00	1.40	1.40
	gasoline	0.50	0.50	9.50	0.30	0.00	0.00	0.00
	propane	0.10	0.00	0.20	0.20	0.00	0.00	0.00
	total	430.40	33.30	264.50	1097.2	1.20	3.00	3.00

Table 303.9b Stationary Reciprocating Engines Emissions (cont) - Point Sources, Industrial (Tons/Year)								
Air Basin	Fuel Type	TOG	ROG	CO	NOx	SOx	PM	PM10
San Diego	distillate oil/ diesel	8.00	5.90	18.90	87.30	1.90	6.30	6.10
	natural gas/ cogeneration	72.90	5.40	20.50	2.50	0.00	0.60	0.60
	total	80.90	11.30	39.40	89.80	1.90	6.90	6.70
San Joaquin	distillate oil/ diesel	11.60	8.50	28.90	115.30	9.90	9.50	9.30
	natural gas	6500.3	481.00	3279.1	7754.2	0.90	51.4	51.10
	natural gas/ cogeneration	3.10	0.20	16.10	127.40	0.00	0.40	0.40
	large bore dual fuel	1.30	0.90	30.20	33.50	1.30	0.00	0.00
	propane	56.90	4.20	18.20	19.80	0.00	0.50	0.50
	total	6573.2	494.9	3372.5	8050.2	12.1	61.8	61.30
S. Central Coast	distillate oil/ diesel	5.20	4.10	15.00	76.20	5.70	5.40	5.30
	natural gas	3630.6	424.10	2877.4	2490.6	13.8	13.9	13.8
	natural gas/ cogeneration	6.20	0.50	18.90	10.90	1.30	0.60	0.60
	gasoline	1.80	1.70	41.80	4.70	0.00	0.30	0.30
	large bore diesel	0.60	0.60	1.60	13.30	1.20	0.50	0.50
	total	3644.4	431.00	2954.7	2595.7	22.0	20.7	20.50
South Coast	distillate oil/ diesel	109.90	80.00	233.50	1007.0	59.3	66.2	63.9
	natural gas	3357.1	247.10	1394.7	4810.2	4.50	0.00	0.00
	natural gas/ cogeneration	90.60	6.70	54.80	105.30	0.00	0.00	0.00
	gasoline	200.60	185.60	3452.8	121.80	4.50	6.00	6.00
	residual/ crude oil	1.40	1.00	1.10	0.00	0.00	0.00	0.00
	propane	313.50	23.00	301.60	352.60	14.1	47.5	46.40
	total	4073.1	543.50	5438.5	6396.9	82.4	119.	116.3

Table 303.9c Stationary Reciprocating Engines Emissions (cont) - Point Sources, Industrial (Tons/Year)								
Air Basin	Fuel Type	TOG	ROG	CO	NOx	SOx	PM	PM10
S. East Desert	distillate oil/ diesel	85.40	62.60	258.80	1197.0	40.9	84.0	82.90
	natural gas	1945.4	338.00	1327.4	9409.5	1.00	23.6	23.4
	gasoline	12.50	11.80	232.90	6.00	0.30	0.30	0.30
	large bore diesel	45.00	43.60	85.00	316.90	15.7	22.0	21.40
	propane	13.80	3.20	0.70	1.00	0.00	0.10	0.10
	total	2102.1	459.20	1904.8	10930.	57.9	130.	128.1
Total	---	17970.	2196.8	15362.	34093.	200.	513.	505.3

Table 303.10 Stationary Reciprocating Engines Emissions - Point Sources, Engine Testing (Tons/Year)								
Air Basin	Fuel Type	TOG	ROG	CO	NOx	SOx	PM	PM10
Bay Area	diesel/ kerosene	0.60	0.40	2.40	9.00	0.60	0.60	0.60
San Diego	diesel/ kerosene	0.10	0.10	0.60	2.40	0.00	0.10	0.1
South Coast	gasoline	0.20	0.20	2.90	0.10	0.00	0.00	0.00
Total	---	0.90	0.70	5.90	11.50	0.60	0.70	0.70

an oxygen concentration in the exhaust that is under 1%. A lean-burn engine operates with an air/fuel ratio that is lean of stoichiometric, and cannot be **adjusted** to operate with an oxygen concentration under 1% in the exhaust.[20]

Four cycle, naturally aspirated spark ignition (SI) engines are rich-burn engines. Two cycle SI engines, compression ignition (diesel and dual fuel) are generally lean-burn engines. With two cycle engines, the scavenge air used to remove exhaust gases from the cylinder increases the oxygen in the exhaust gases.

Table 303.11a Stationary Reciprocating Engines Emissions - Point Sources, Commercial-Institutional (Tons/Year)								
Air Basin	Fuel Type	TOG	ROG	CO	NOx	SOx	PM	PM10
Bay Area	distillate oil/ diesel	3.50	2.60	9.70	44.90	4.40	3.10	3.00
	natural gas	187.40	13.90	492.10	246.30	0.40	10.8	10.70
	total	190.90	16.40	501.80	291.20	4.80	13.9	13.80
N. Central Coast	distillate oil/ diesel	0.10	0.10	0.20	0.90	0.10	0.10	0.10
	natural gas/ cogeneratio	69.30	5.10	32.60	16.10	0.00	1.40	1.40
	total	69.40	5.20	32.80	17.00	0.10	1.50	1.50
Sacramento	distillate oil/ diesel	1.50	1.10	3.40	15.80	0.90	1.10	1.10
	natural gas	97.90	7.20	33.70	257.80	0.00	0.00	0.00
	gasoline	0.40	0.40	11.70	0.30	0.00	0.00	0.00
	propane	2.70	0.20	81.60	1.30	0.10	0.10	0.1
	total	102.50	8.90	130.40	275.20	1.00	1.20	1.20
San Diego	distillate oil/ diesel	24.30	17.80	57.30	273.00	4.70	15.3	14.90
	natural gas	0.00	0.00	0.10	0.50	0.00	0.00	0.00
	natural gas/ cogeneratio	574.00	42.50	406.90	327.10	0.00	6.80	6.80
	process gas	27.90	4.90	96.30	31.50	23.3	1.80	1.80
	total	626.20	65.20	560.60	632.10	28.0	23.9	23.50

Table 303.11b Stationary Reciprocating Engines Emissions - Point Sources, Commercial-Institutional (Tons/Year) (Continued)

Air Basin	Fuel Type	TOG	ROG	CO	NOx	SOx	PM	PM10
San Joaquin	distillate oil/ diesel	0.50	0.40	1.20	5.80	0.50	0.50	0.50
	natural gas	23.00	1.70	37.50	43.50	0.10	0.90	0.90
	propane	5.20	0.40	1.90	2.00	0.00	0.10	0.10
	total	28.70	2.50	40.60	51.30	0.60	1.50	1.50
S. Central Coast	distillate oil/ diesel	14.30	11.20	45.70	178.70	7.70	14.2	13.90
	natural gas	62.60	6.70	238.40	125.60	0.50	0.20	0.20
	natural gas/ cogeneration	0.30	0.00	25.00	2.20	0.00	0.00	0.00
	gasoline	0.10	0.10	6.90	0.10	0.00	0.00	0.00
	total	77.30	18.00	316.00	306.60	8.20	14.4	14.1
South Coast	distillate oil/ diesel	60.20	44.00	127.00	585.40	40.2	41.2	40.00
	natural gas	286.20	21.20	510.60	386.70	0.00	0.00	0.00
	gasoline	124.40	118.20	2251.9	63.70	2.60	3.50	3.50
	process gas	162.60	10.50	708.10	189.50	4.80	3.50	3.10
	propane	7.70	0.50	1.30	1.40	0.00	0.00	0.00
	total	641.10	194.30	3598.9	1226.7	47.6	48.2	46.60
S. E. Desert	distillate oil/ diesel	12.70	9.50	27.60	123.70	9.80	10.1	9.90
	natural gas	12.40	1.00	12.30	67.70	0.00	0.10	0.10
	natural gas/ cogeneration	0.80	0.20	2.90	22.60	0.00	0.00	0.00
	gasoline	25.30	24.30	482.60	12.50	0.60	0.80	0.80
	process gas	0.80	0.10	2.70	1.30	0.00	0.00	0.00
	total	52.00	35.00	528.10	227.80	10.4	11.0	10.80
Total	—	1788.1	345.60	5709.2	3027.9	100.	115.	112.8

Table 303.12 Average NOx Emissions from Reciprocating Engines							
Engine type	# of engines in database	Power (hp)	Average heat rate (Btu/hp-hr)	Uncontrolled NOx emissions			
				High (g/hp-hr)	Low (g/hp-hr)	Average	
						(g/hp-hr)	(lbm/MMBtu)
Rich burn (SI)	8	0-200	8140	15.8	9.1	13.1	3.54
	13	201-400	7820	23.5	9.1	16.4	4.62
	31	401-1000	7540	22.4	10.4	16.3	4.76
	19	1001-200	7460	25.0	13.0	16.3	4.81
	10	2001-400	6780	18.0	13.0	15.0	4.87
	2	4000+	6680	14.0	14.0	14.0	4.62
Lean burn (SI)	7	0-400	8760	17.5	3.0	7.9	1.99
	17	401-1000	7660	27.0	15.5	18.6	5.35
	43	1001-200	7490	27.0	14.0	17.8	5.23
	30	2001-400	7020	27.0	10.0	17.2	5.40
	25	4001+	6660	17.5	10.0	16.5	5.46
Diesel (CI)	12	0-200	6740	17.1	10.0	11.2	3.66
	8	201-400	6600	19.0	7.6	11.8	3.94
	22	401-1000	6790	19.0	9.0	13.0	4.22
	14	1001-200	6740	19.0	8.5	11.4	3.73
	6	2001-400	6710	14.0	9.3	11.4	3.74
	6	4000+	6300	12.0	12.0	12.0	4.20
Dual fuel (CI)	5	700-1200	6920	13.0	9.3	10.0	3.18
	3	1201-200	7220	13.0	6.2	10.7	3.26
	5	2001-400	6810	13.0	5.0	8.4	2.72
	4	4000+	6150	5.0	4.5	4.9	1.75

304 EMISSION CONTROL SYSTEMS FOR RECIPROCATING ENGINES

The main methods available for the control of emissions from reciprocating engines include positive crankcase ventilation, adjusting the air/fuel ratio, ignition timing retard, adjusting both air/fuel ratio and ignition timing retard, selective catalytic reduction, non-selective catalytic reduction, prestratified charge and low emission combustion. Some newer and less widely used control technologies will also be discussed. These systems are primarily aimed at the reduction of NOx emissions. NOx control systems can be categorized by being a "front end" control or a "back end" control. A front end control is an attempt to control NOx emissions by preventing them from forming during combustion.

300 EMISSION CONTROL

A back end NOx control is an attempt to convert NOx emissions (NO and NO_2) back to N_2, the natural form of nitrogen in the atmosphere.

304.1 POSITIVE CRANKCASE VENTILATION

Positive crankcase ventilation (PCV) is a system for control of emissions from the blowby of gases past the piston rings that occurs during the compression and power strokes of an engine (Fig. 304.1, 304.2). These blowby gases contain unburned fuel (hydrocarbons). Before positive crankcase ventilation, engines were equipped with a draft tube that allowed blowby gases to exit the crankcase and enter the atmosphere. If crankcase gases are allowed to build up in an engine, varnish and sludge deposits develop and will shorten the life of the engine.

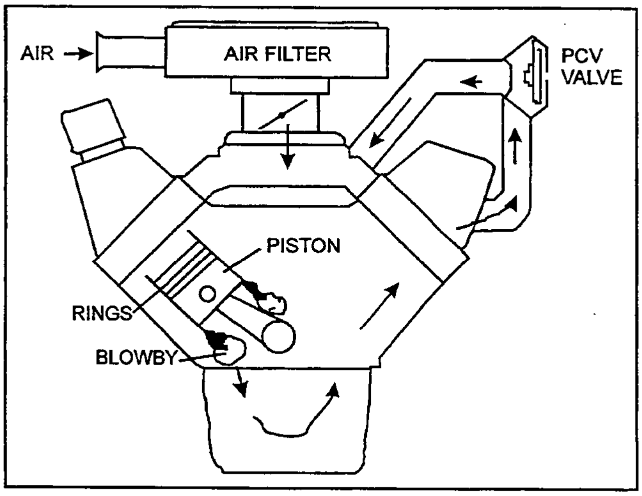

Figure 304.1 Positive Crankcase Ventilation

PCV Valve

The blowby gases are prevented from entering the atmosphere by PCV. The system consists of a hose that leads from the crankcase to the intake manifold and the PCV valve. When blowby gases begin to build up in the crankcase, the PCV valve allows them to flow from the crankcase to the intake manifold. The gases are then drawn into the cylinder with a fresh air and fuel charge and oxidized.

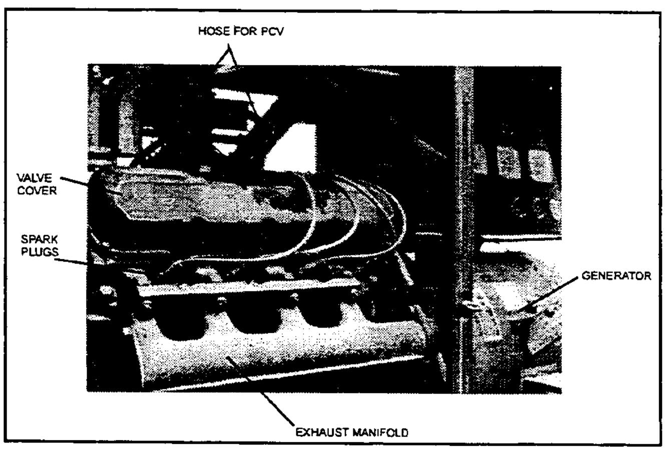

Figure 304.2 Engine with PCV Controls

304.2 AIR/FUEL RATIO

In order to reduce NOx emissions, the air/fuel ratio can be adjusted to reduce NOx emissions. From Figure 302.1 it can be seen that the maximum NOx is produced just above (lean of) stoichiometric. Unfortunately, the point where the maximum NOx is produced is close to the point where the maximum efficiency in terms of brake specific fuel consumption occurs. It is also close to the point of maximum combustion temperature. NOx can be reduced by moving the air/fuel ratio away from this peak.

The air/fuel ratio can be manually adjusted in the field, but the use of an automatic feedback controller is a requirement for most engines to maintain precise control of the air/fuel ratio. The automatic feedback controller keeps the air/fuel ratio properly adjusted to reduce NOx emissions while the engine undergoes changes in load, speed and ambient conditions. The automatic air/fuel controller also helps avoid the occurrence of detonation and lean misfire from changes in engine operation.

In turbocharged engines the air/fuel ratio adjustments normally use an exhaust bypass system with a regulator valve to control the air flow delivered by the turbocharger.

Figure 302.1 shows that as an engine operates in the rich area of air/fuel ratios burning natural gas, emissions of NOx will be lowered, but carbon monoxide emissions will increase.[21] This is due to the absence of oxygen, which lowers the temperatures of combustion, reducing NOx emissions. Enriching the air/fuel mixture will also lower the temperature of the exhaust emissions. Carbon monoxide increases from incomplete combustion and hydrocarbon emissions will also increase. Another problem with a richer air/fuel mixture is that the brake specific fuel consumption (Bsfc) will increase. This causes an increase in fuel use, but the engine will respond better to load changes. These factors limit how far the air/fuel ratio can be made richer to reduce NOx.

For lean-burn engines, increasing the air/fuel ratio will reduce NOx emissions as long as the air/fuel ratio is beyond the peak in the NOx curve. With more air in the cylinder, the air/fuel mixture has a high capacity to hold the heat of combustion. The temperature in the cylinder will be lower, so less NOx is produced. Adjustment of the air/fuel ratio is typically not a method of air pollution control for lean-burn, two cycle pump-scavenged or blower scavenged engines. Some of these engines may operate near stoichiometric with air/fuel ratios beneath the NOx peak, so increasing the air/fuel ratio would increase NOx.

To create a leaner mixture, more air can be added to the engine or less fuel can be injected. On a naturally aspirated engine a turbocharger can be added to increase the air in the charge. If the engine already has a turbocharger, it may be replaced or modified by the addition or adjustment of the air regulator system. For fuel injected engines the fuel injectors for each cylinder can be adjusted to reduce the fuel. In carbureted engines, the air/fuel ratio may vary between different cylinders because of less than ideal distribution of air and fuel in the intake manifold. This could cause the lean misfire limit to be surpassed in any cylinder, so the air/fuel ratio can be set higher (leaner) for fuel injected engines.[22]

Lean Flammability Limit

The amount that the air/fuel ratio can be increased on any lean-burn engine is limited by the lean flammability limit. As the limit is approached NOx emissions are reduced, but combustion will begin to become unstable and engine misfire could occur. The lean flammability limit will vary between different engines, even within the same model. When the lean flammability limit is reached misfire can occur, resulting in fuel being released from the exhaust without being burned. Once the air/fuel ratio has been leaned to produce a minimum of hydrocarbon emissions, the hydrocarbon emissions will increase with further leaning. This occurs from the reduced combustion temperatures.

Leaning the air/fuel mixture makes it harder to ignite. In order to counter these effects a higher energy ignition system is needed for spark ignition engines, for a longer-lasting higher voltage spark.

It is usually preferred to operate an engine lean rather than rich, since fuel efficiency is higher on the lean side. Enriching the air/fuel ratio increases carbon monoxide emissions, but leaning it decreases all the emissions. If a mixture is continually leaned a point will be reached where fuel consumption will begin to increase instead of decrease.

In general, when leaning an engine beyond the NOx peak there is approximately a 5% decrease in NOx for every 1% increase in intake air. The rate of NOx reduction decreases as the mixture becomes leaner. Table 304.1 shows emission reductions attained by adjusting the air/fuel ratio on seven rich-burn medium speed engines.[23] NOx emissions were reduced to a range between 1.52 g/hp-hr and 5.70 g/hp-hr, which is a reduction of emissions ranging between 10 and

72%. The average uncontrolled NOx emissions were 7.2 g/hp-hr, the average controlled NOx emissions were 3.89 g/hp-hr, so the average emission reduction was 45%.

Table 304.1 NOx Reductions from Air Fuel Ratio Adjustment on Rich Burn Engines

Engine #	Power (hp)	Uncontrolled Emissions		Controlled Emissions		% Reduction
		g/hp-hr	ppmv	g/hp-hr	ppmv	
1	620	10.5	3060	5.38	1560	49
2	620	10.7	1560	5.70	830	47
3	450	7.9	1970	3.76	1050	47
4	620	5.4	814	1.52	228	72
5	620	5.4	857	3.71	591	31
6	620	5.4	805	2.30	346	57
7	620	5.4	901	4.84	812	10
Average	----	7.2		3.89		45

Table 304.2 shows emission data for NOx, hydrocarbon and carbon monoxide emissions from a Waukesha engine. The data shows that when enriching the mixture to reduce NOx emissions, hydrocarbon emissions only increase a small amount from 0.2 to 0.3 g/hp-hr, but carbon monoxide emissions rise from 1.0 to 33.0 g/hp-hr as the air/fuel ratio is adjusted from the leanest to the richest measured.[24]

Table 304.2 Carbon Monoxide and Hydrocarbon Emissions

Model Series	Richest Air/Fuel Ratio			Leanest Air/Fuel Ratio			Air/Fuel Ratio Mass Basis	
	NOx	CO	HC	NOx	CO	HC	Richest	Leanest
1	7	28.0	0.3	18.0	1.0	0.2	15.5:1	17:1
2	10.0	25.0	0.3	25.0	0.5	0.2	15.5:1	18:1
3	8.3	34.0	0.4	20.7	0.8	0.3	15.5:1	17.4:1
4	8.0	30.5	0.2	24.0	0.6	0.1	15.5:1	18:1
5	8.5	35.0	0.4	20.0	1.0	0.2	15.5:1	17:1
6	7.0	34.0	0.3	16.0	1.0	0.3	15.5:1	17:1
7	7.5	45.0	0.4	11.0	2.0	0.3	15.15:1	17:1
Average	8.0	33.0	0.3	19.2	1.0	0.2		

The amount of emission control from adjustment of the air/fuel ratio varies between different engines even when they are from the same model. In general, varying the air/fuel ratio can reduce NOx emissions 10 to 40%.[25]

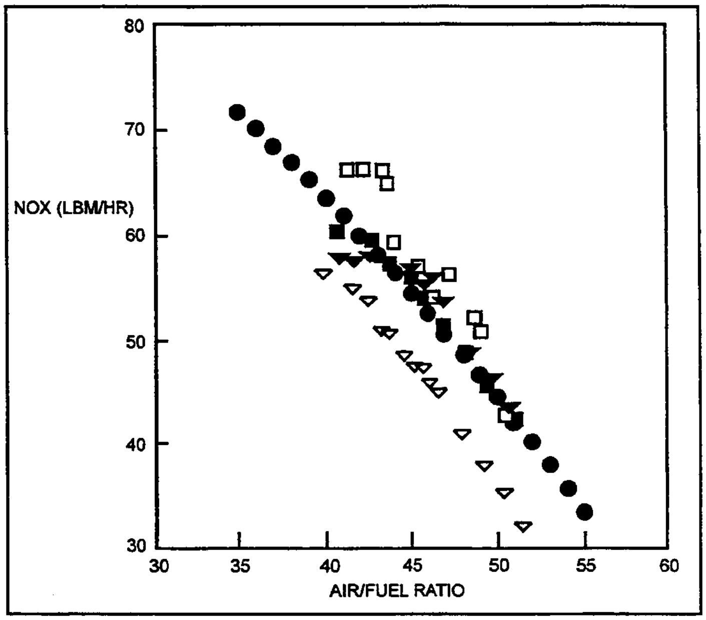

Figure 304.3 NOx Emissions vs. Air/Fuel Ratio

Figure 304.3 shows how NOx emissions decrease in four identical lean burn engines from increases in the air/fuel ratio.[26] The uniform plot of filled circles is a composite derived from empirical data and does not consider whether the air/fuel ratios are achievable. The remaining data points are from experimental data. Also, the air/fuel ratios presented include the total of combustion air and scavenging air, which is why the ratios are so high. The NOx reduction from the four engines ranges from 20 to 33%. Other tests have shown that increases in the air/fuel ratio increase carbon monoxide and hydrocarbons a limited amount and create a small percent increase in Bsfc (brake specific fuel consumption).

304.3 IGNITION TIMING

Retarding Ignition Timing Reduces NOx Emissions

In spark ignition engines the timing of the spark can be advanced or retarded, and in a similar manner for diesel engines the timing of the ignition can be controlled by the timing of the injection of the fuel. Advancing the spark or the injection of the fuel (diesel engines) causes the peak pressure and temperature from combustion to occur closer to top dead center. This causes the temperature and pressure to be higher and increases NOx emissions. If the spark or the injection of fuel is retarded, the peak pressure and temperature from combustion occur later, when the piston has moved further from top dead center. The larger volume of the cylinder absorbs more of the heat of the combustion and the residence time is reduced. The pressure and temperature in the cylinder will be reduced and therefore the NOx emissions will be lowered.

Retarding the ignition timing can have some adverse effects on engine performance. The temperature of the exhaust will be higher and this can adversely affect the exhaust valves. The higher temperatures can cause the valve materials to deteriorate over time. If the engine has a turbocharger, it could be adversely affected by the change in the exhaust. The power output decreases and the brake specific fuel consumption increases so the fuel economy drops. All these problems generally limit the retarding of ignition to between 4 and 6 degrees for spark ignition engines. When the timing is retarded, effects on other engine parameters must be examined, because serious damage to the engine could occur.

Diesel Engines

In diesel engines, retarding the timing increases black smoke and white smoke. White smoke is also called cold smoke because it occurs during engine startup. Cold starts, especially at lower atmospheric temperatures, are more difficult. The maximum timing retard in diesel engines is generally limited to 8 degrees from the standard setting.

Retarding the timing is generally a more effective emission control for compression ignition engines than spark ignition engines. SI engines are more sensitive to the changes in engine operation from timing retard. Excessive timing retard will cause misfire and poor operation.

As with air/fuel ratio, the ignition timing can be adjusted in the field. Most engines are equipped with an electronic ignition system which allows the timing to be automatically adjusted. As the load and speed of the engine changes, the timing will adjust to give the best performance and emission reduction.

NOx reductions attained by adjustment of the ignition timing vary between different models of an engine and between different engine speeds. For example, an engine that operates at a speed between 500 and 1000 rpm with a retarding of 2 to 4 degrees will probably have a greater NOx reduction than an engine operating at a speed between 2000 and 3000 rpm. Figure 304.4 illustrates a plot of manufacturer data for a rich burn engine with a 5° retard. NOx reductions vary depending on the air/fuel ratio. At an air/fuel ratio of about 102%, a 5° retard yields about a 10% reduction in NOx emissions. At a ratio of about 96%, a 5° retard provides a NOx reduction of about 40%.[27]

Figure 304.5 illustrates emissions from four lean burn engines with timing retard. These tests had NOx emissions reductions approximately between 3 and 15%.[28] Manufacturer data for diesel engines indicates a 20 to 30% reduction in

NOx emissions for diesel engines.[29]

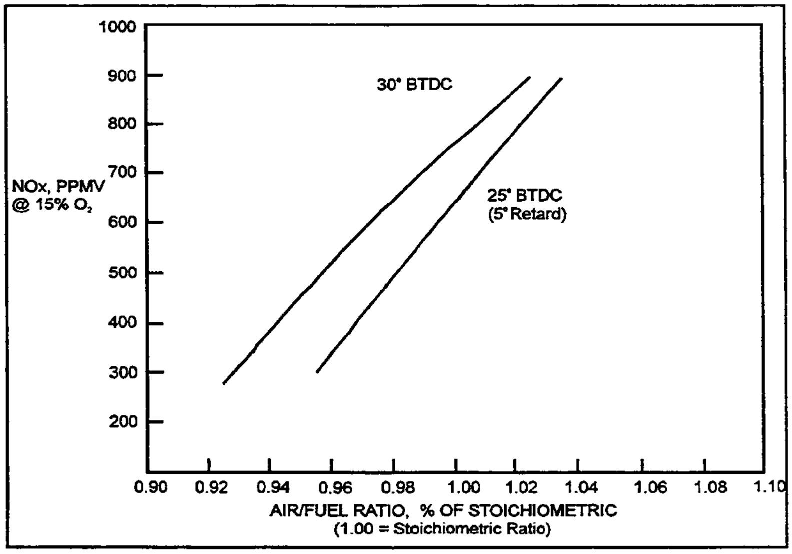

Figure 304.4 NOx Reductions with Ignition Retard

Emissions of carbon monoxide and hydrocarbons may increase or decrease a small amount from ignition retard. The higher exhaust temperature resulting from it tends to oxidize any unburned hydrocarbons or carbon monoxide left in the exhaust from the reduced residence time of combustion. The brake specific fuel consumption will increase with more ignition retard and the overall increase may be as high as a few percent.

304.4 ADJUSTING AIR/FUEL RATIO AND IGNITION TIMING IN CONJUNCTION

Some engines may be able to attain NOx emission reductions while reducing some of the undesirable effects on performance of adjusting the air/fuel ratio or ignition timing by adjusting both of them in conjunction. Figure 304.4 shows that applying a reduction in air/fuel ratio and retarding the ignition timing reduces emissions. Reducing the

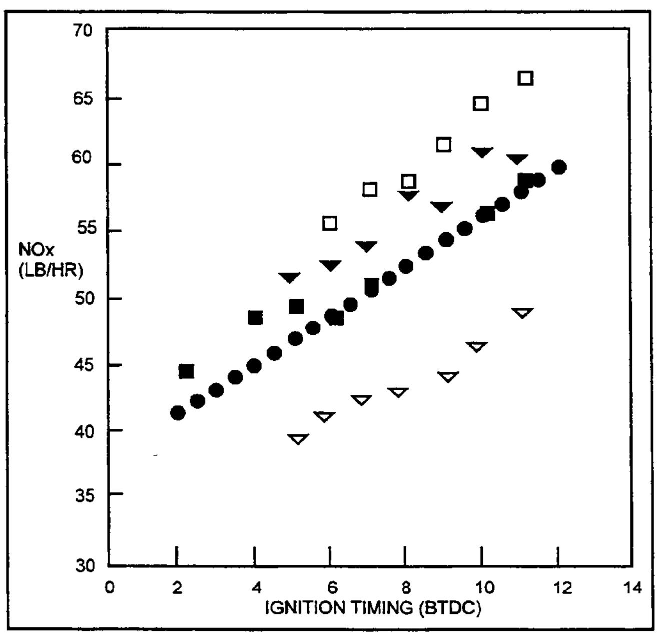

Figure 304.5 NOx vs. Ignition Retard for Lean Burn Engines

air/fuel ratio on rich burn engines increases carbon monoxide, but by retarding the timing the exhaust temperatures will increase and the higher temperatures will tend to oxidize the carbon monoxide.

NOx reductions from some tests of lean burn engines are shown in Table 304.3.[30] The NOx reductions vary, even though most of the engines are from the same model. The NOx reduction ranges from 2.7 to 48% and the average is 25%. The manufacturer of engines #1-6 estimates that NOx reductions will be between 20 and 35% with these combined NOx control techniques, with an increase of brake specific fuel consumption under 5%. The estimated maximum reduction of NOx from adjustment of air/fuel ratio or ignition timing is 12 to 25%. The reductions from these methods of control aren't cumulative, but they are slightly higher than reductions from just fuel ratio or ignition timing.

Table 304.3 NOx Reductions for Lean Burn Engines with a Combination of Air fuel Ratio and Ignition Timing Adjustment

Engine #	Manufacturer	Model	Power (hp)	% NOx Reduction
1	Dresser-Rand	RA32	300	25
2	Dresser-Rand	RA32	300	2.7
3	Dresser-Rand	RA32	300	48
4	Dresser-Rand	RA32	300	27
5	Dresser-Rand	RA32	300	26
6	Dresser-Rand	RA32	300	39
7	Cooper-Bessem	----	600	8.4
Average	-----			25

304.5 PRESTRATIFIED CHARGE

Prestratified charge (PSC) was developed and patented by Cornell University and was first used on automobiles in the late 1970's. It was adapted for use with stationary engines in the mid 1980's. PSC is a method of controlling NOx emissions by using a layered or stratified charge in the combustion chamber

(Fig. 304.6). The stratification produces an ignitable mixture near the spark plug, but a leaner mixture elsewhere. The richer mixture near the spark plug starts ignition and allows combustion to proceed throughout the rest of the cylinder with a decreased chance of misfire. Since the air/fuel mixture is very lean and the temperature of combustion is reduced, NOx emissions are lowered.

Reduced NOx Emissions

Prestratified charge is available as an add-on control device for rich burn engines that are naturally aspirated, carbureted, or turbocharged, and have no intake/exhaust overlap. Blower scavenged engines cannot use prestratified charge and only four cycle engines can use PSC. Some fuel injected engines cannot use PSC since the spray of the injectors would disturb the stratification of the charge. One method of retrofitting an engine's injectors involves using injectors that inject pulses of air so that layers of air and air/fuel mixture are created. Once inside the combustion chamber, the mixture near the spark plug will be rich, the next layer may be an inert gas layer from exhaust gas recirculation, and the bottom layer will be air. PSC works well as a NOx control on digester, landfill and natural gas fueled engines that operate with a constant power output, and it has been applied to some engines operating with cyclic loads.

Prestratified charge kits are available and the kits generally consist of intake manifolds, air hoses, air filters, control valves, and mechanical linkages connected to the carburetor or a microprocessor-based control system. Kits are generally available for all applicable engines with a power rating over 100 hp.

Other Effects

As with other control options, the amount of emission reductions from prestratified charge must be balanced with the negative attributes of using it. NOx reductions from PSC are limited by increases in carbon monoxide and hydrocarbon emissions, decrease in power output (power derate), increases in the brake specific fuel consumption, and the quantity of air that can be induced in the intake manifold vacuum. The increases in carbon monoxide and hydrocarbons are due to incomplete combustion from the quenching effect of the cooler walls of the combustion chamber. This occurs from the decrease in temperatures in the cylinder from the very lean air/fuel mixtures.

Engines with prestratified charge fired with fuels that have a relatively large amount of carbon dioxide (CO_2) in them, such as digester gas or landfill gas, have a smaller impact on carbon monoxide (CO) emissions. In some cases a decrease in carbon monoxide emissions was noted with PSC and use of high carbon dioxide fuels.

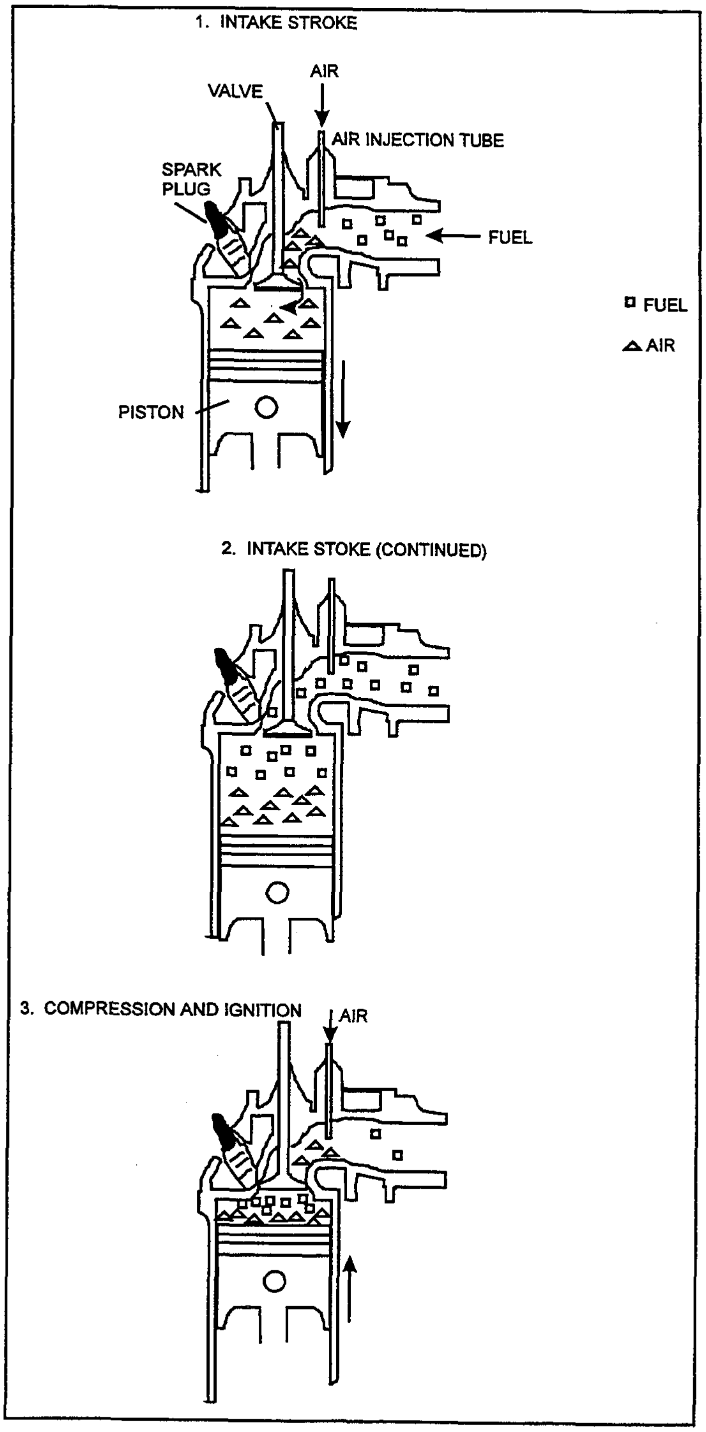

Figure 304.6 Prestratified Charge

300 EMISSION CONTROL

Reductions in NOx emissions of over 80% are achievable with prestratified charge when an engine operates with air injection and less than 70% of its rated power. With the injection of exhaust gas, an engine may attain 80% NOx reduction and operate at 70 to 80% of its rated power. In order to operate an engine in excess of 80% of its rated power with PSC to maintain an 80% reduction in NOx, a turbocharger may be required. The turbocharger helps recover power lost from the PSC controls.[31]

The main advantages of the PSC system are that it is low in cost, the fuel economy is good, it has low maintenance, and it is not sensitive to the type of fuel used. With PSC an engine can operate within a few percent of the setting for best fuel economy. The PSC system has only two moving parts and there is no catalyst that needs replacing. However, the main disadvantage of PSC is that it lowers the power output.

According to a vendor of PSC the power reduction (power derate) ranges from 15 to 20% for naturally aspirated engines and 0 to 5% for turbocharged engines. In general, with prestratified charge emissions can be brought down to 2 g/hp-hr, but it may be reduced as low as 1.0 g/hp-hr in some engines. Bringing emissions down to this level reduces the power output 25% in naturally aspirated engines and 10% in turbocharged engines.[32] The decrease in power is due to the carburetor charge being displaced by air in the intake manifold. The leaner charge has a lower power output. The decrease in power output for existing naturally aspirated engines can be reduced to 5 to 10% by adding a turbocharger. If an engine operates below its rated power output, the reduction in maximum horsepower from PSC may not matter. For example, if the rated horsepower is 100 hp, but it operates in an application requiring 80 hp, the reduction in maximum power output does not affect the engine.

Moderate reductions in NOx emissions ranging approximately between 4.0 to 7.0 g/hp-hr cause a reduction as high as 2% in the brake specific fuel consumption. On the other hand, with higher emission reductions the Bsfc may increase as much as 2% over the level without any controls.

Table 304.4 illustrates emissions from test runs done on engines in the South Coast AQMD using prestratified charge.[33] Note how in every test except one that there is a substantial increase in carbon monoxide emissions. NOx emission reductions ranged from 79% to 91%.

Table 304.4 Emissions Using PSC from Several Engines in the South Coast AQMD											
No.	Power (hp)	NOx Emissions				CO Emissions				% Change	
		PSC off		PSC on		PSC off		PSC on		NOx	CO
		ppmv	g/hp-hr	ppmv	g/hp-hr	ppmv	g/hp-hr	ppmv	g/hp-hr	-89	42
1	870	1660	24.7	157	2.2	113	1.0	184	1.5	-91	63
2	420	1490	22.2	234	3.2	96	0.9	169	1.4	-84	76
3	–	1160	17.3	243	3.3	139	1.3	174	1.5	-79	25
4	420	961	14.3	179	2.5	136	1.2	184	1.5	-81	35
5	141	930	13.9	101	1.4	99	0.9	139	1.2	-89	40
6	141	888	13.3	83	1.1	92	0.8	155	1.3	-91	68
7	–	783	11.7	116	1.6	691	6.3	137	1.1	-85	-80

304.6 SELECTIVE CATALYTIC REDUCTION (SCR)

NOx Emissions Reduction

Selective Catalytic Reduction (SCR) is a back-end method of controlling NOx emissions that was first patented by a U.S. company in 1959 and further developed by Japanese and German manufacturers in the 1970s. It was originally developed for the control of NOx emissions from coal fired boilers in power plants. SCR is not used on many reciprocating engines; it is primarily used to control NOx emissions from boilers and gas turbines. Using SCR can reduce NOx emissions by over 90%.

The selective catalytic reduction process basically works by using ammonia (NH_3) as a reagent, injecting it into the flue gas (exhaust) of the engine, plus the use of a catalyst (Fig. 304.7). The ammonia and NOx emissions react in the presence of the catalyst to form nitrogen (N_2) and water. Atmospheric nitrogen is usually in its diatomic form of N_2 and the water is non-polluting. The ammonia is injected into the process with air or steam.

Oxygen is also required for the chemical reactions for SCR. It works well as a NOx control only for lean burn engines, since they operate with relatively high air/fuel ratios and there is more oxygen in the exhaust. Rich burn engines do not have enough oxygen in the exhaust. The primary chemical reactions that occur in SCR are shown below.[34]

$$6NO + 4NH_3 \rightarrow 5N_2 + 6H_2O$$

$$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O$$

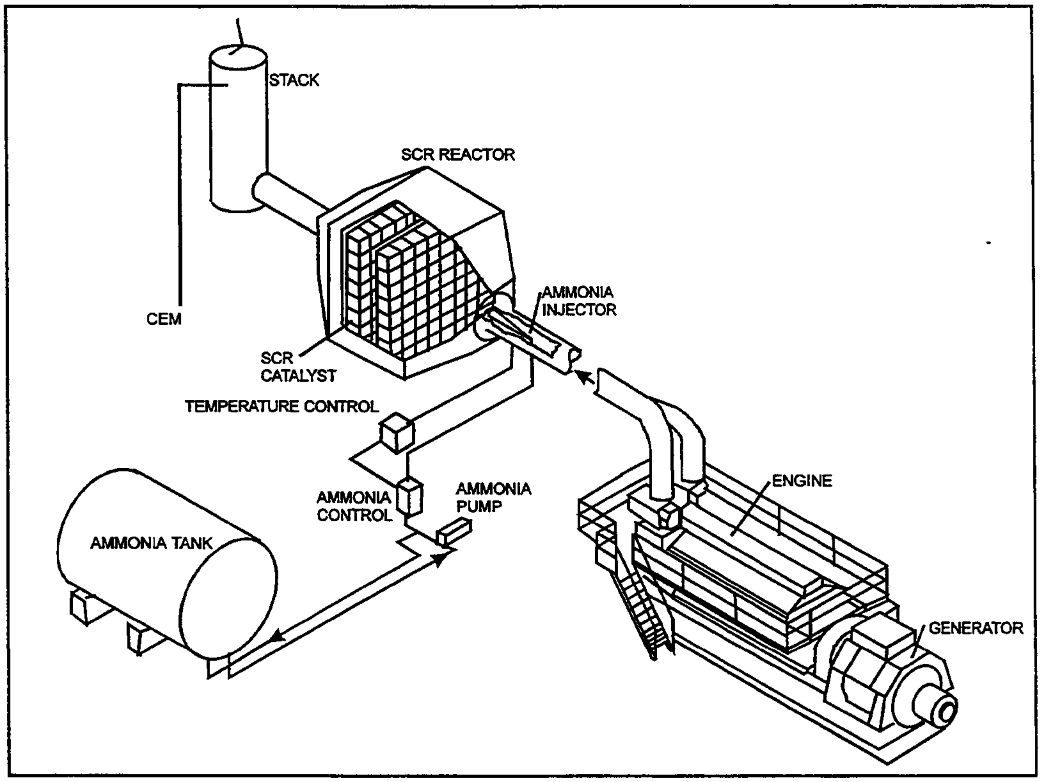

Figure 304.7 Major Parts of SCR System

304.6.1 SCR Catalysts

The heart of a selective catalytic reduction system is the catalyst. The reaction converting NOx to nitrogen and water occurs on the surface of the catalyst. NOx compounds must come into contact with the catalyst in order to be converted. Older catalysts were in the form of small pellets. Today, catalysts are usually made in the form of honeycomb structures.

In the honeycomb type of catalyst, the size of the openings in the catalyst is an important parameter. This parameter is called the pitch and it is gauged by the center to center distance between the adjacent openings in the catalyst. The smaller the pitch is, the larger the catalyst surface area will be. The surface area of the catalyst is maximized, since compounds must come into contact with it to convert NOx to nitrogen. On the other hand, the smaller the openings in the catalyst are, the more prone the catalyst is to being plugged from contaminants, and the back pressure will be higher.

The residence time of flue gases in the catalyst must be long enough for NOx compounds to be converted to nitrogen. As with the three T's of combustion (time, temperature, and turbulence) a longer time in the catalyst is better for NOx removal. The residence time is the volume of the catalyst "reactor" (i.e. ft^3) divided by the volume flow rate (i.e. ft^3/sec). Having a larger catalyst volume or a lower volume flow rate helps increase residence time. The inverse of the residence time is the space velocity.

There are two ways in which the catalyst is built. A homogenous mixture containing the catalyst materials may be extruded into the catalyst shape. This is often done for zeolite catalysts. The second way to make the catalyst is to "wash-coat" the catalyst substrate with the catalyst material. The catalyst material then bonds to the substrate.[35] The substrate acts as a support structure for the catalyst.

Catalyst Materials

Most systems use "metal based" catalysts for selective catalytic reduction. The most common ones are vanadium pentoxide (V_2O_5), titanium dioxide (TiO_2), tungsten trioxide (WO_3), aluminum oxide (Al_2O_3), platinum and other noble metals. Most metal-based catalysts are often applied to the catalyst substrate as a wash-coat and vanadium pentoxide is one of the most common metal-based catalysts. Aluminum oxide was the main catalyst material used in older selective catalytic reduction systems. Tungsten trioxide is not used as much as vanadium pentoxide and titanium dioxide. The titanium dioxide catalyst has a larger operating temperature range than aluminum oxide, but about 1/5 the area of aluminum oxide for the reaction.

New, better performing catalysts are still being developed. Newer catalysts and fabrication methods are yielding catalysts with larger temperature operating ranges and increased resistance to erosion, poisoning and blinding.[36] Zeolites are a class of catalyst that are making their way into SCR systems. Zeolite catalysts contain lower amounts of metals, which decreases potential contamination of soil and groundwater when the catalyst is disposed of. Aluminum silicates, a type of zeolite, can operate with temperatures up to 1100°F, which is about 300°F higher than many metal catalysts. The use of zeolite catalyst could eventually reduce the cost of SCR systems, increase the reactivity of the catalyst, and reduce emissions of ammonia (ammonia slip). Unlike base metal catalysts, zeolite catalysts usually form the structure and the active surface of the catalyst.

Ammonia Slip

Zeolite catalysts have a very porous crystalline structure. One gram of zeolite catalyst may have 3,000 ft^2 of catalyst surface. In the zeolite catalyst the chemical reaction to reduce NOx does not occur on the catalyst surface. The chemical reaction occurs in the molecular sieve of the crystalline structure. NOx compounds and ammonia diffuse into molecular-sized cavities and the products of the reaction are then expelled. The motion of the expelled compounds tends to clean the catalyst. The reduction of NOx occurs within the molecular sieve while masking and poisoning occurs more on the outside of the catalyst. This helps make zeolites resistant to masking and poisoning.

Iron oxides are another class of catalyst that has been tested in Germany. Iron oxide catalysts can operate at relatively high temperatures, but the catalyst requires a large volume. Activated carbon, which has been used to control volatile organic compounds for many years, is a new type of catalyst that has been commercially demonstrated in Germany and Japan.[37]

Operating experience illustrates that the selective catalytic reduction catalyst will usually last at least 6 years for systems using distillate oil. Most manufacturers of the catalyst give at least five year warranties on them. Over time the effectiveness of the catalyst declines. The replacement of the catalyst is expensive.

Catalyst Disposal

Many catalyst materials contain heavy metal oxides which are hazardous to human health. Vanadium pentoxide, for example, is on the Environmental Protection Agency's list of Extremely Hazardous Substances. In California, spent catalyst from SCR is considered to be hazardous waste and the volume of wastes from SCR are large. The disposal of catalyst is expensive, but some catalyst manufacturers provide for disposal and/or recycling of the catalyst. In some cases spent catalyst can be used for other operations. In Japan, for example, titanium from titanium dioxide spent catalyst is used for paint pigment. An advantage of precious metal catalysts is that they do not produce as much hazardous waste, and they have a salvage value at the end of their useful life, but initial cost is higher.

Catalyst Masking and Poisoning

Particulates, ammonium salts, sulfur, chlorine and chloride, and other substances can deposit on the surface of the catalyst and inhibit catalyst activity by forming a barrier between the exhaust gas and the catalyst. Masking agents can usually be removed by vacuuming, soot blowing or by using steam. Over 90% of the catalyst activity can be regained by removing masking agents. Poisoning agents chemically react with the catalyst and render it inactive. Catalyst poisoning is permanent and the effects of it can only be improved by replacing the catalyst.

The source of masking and poisoning agents is usually the fuel or the lubricating oil. Natural gas is usually free of masking and poisoning agents, but digester gas, landfill gas, coal gas, distillate oil, and refinery gas fuels often contain contaminants. For distillate oils, particulates and heavy metals are potentially damaging to the catalyst.

Any lubricating oil that burns can create emissions that can foul the catalyst. The main items in lubricating oil that can cause this problem are ash and phosphorus. Oils with a low content of ash and phosphorus are available and they are recommended for many engines using SCR. The primary problem with oils low in ash and phosphorus is that life of the exhaust valves in four cycle engines may be reduced as much as 50%.[38] Newer oils have been formulated to reduce this problem.

The leading edge of the catalyst is more subject to erosion and masking, especially if there is any dust or particulate present. Diesel engines have more particulates and heavy hydrocarbons in their exhaust. Dummy layers of catalyst or a guard bed can be used to reduce the effects of erosion and masking. The guard bed has the same structure as the catalyst material and it is usually installed upstream of the catalyst body. The face of the catalyst may be periodically vacuumed to remove particulate matter.

304.6.2 Temperature Control for SCR

The chemical reactions that take place in selective catalytic reduction occur over a small temperature range. For a selective catalytic reduction system operating with a vanadium pentoxide catalyst, the allowable temperature range is generally between 600 to 800°F (Fig. 304.8) . It is important to keep the temperature of the reaction in this temperature range because if it drops below 600°F, the reaction efficiency becomes too low and excessive amounts of ammonia will be released out of the stack. If the reaction temperature gets too high the catalyst may start to decompose. Furthermore, ammonia will begin to decompose at temperatures above 850°F. Some high temperature zeolite catalysts which can operate at temperatures up to 1100°F have become available.[39]

304.6.3 Effects of Sulfur Compounds with SCR

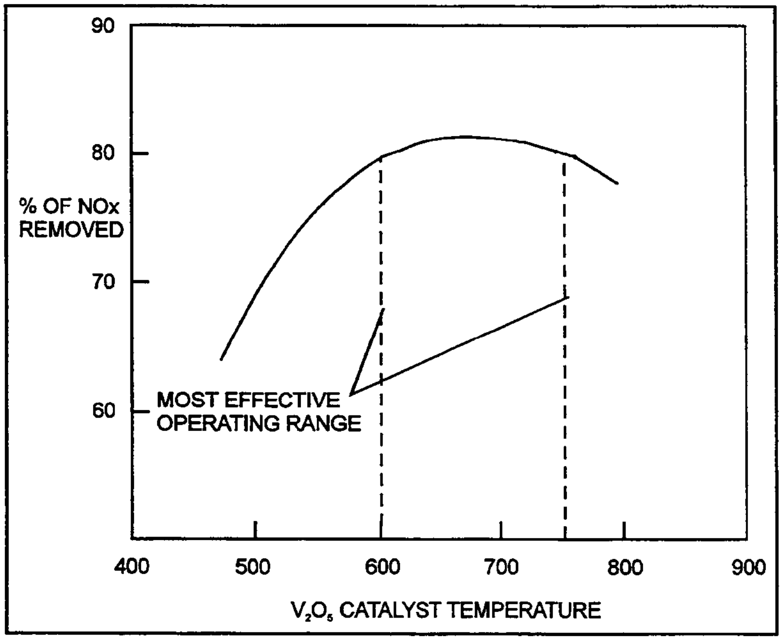

Figure 304.8 % NOx Removed vs. Vanadium Pentoxide Catalyst Temperature

Ammonium Salts/ Particulate Formation

Systems that use selective catalytic reduction to control NOx emissions and use a fuel containing sulfur may have several problems. After the sulfur in a fuel burns in the engine, forming sulfur dioxide (SO_2), the SCR catalyst may oxidize the sulfur dioxide to sulfur trioxide (SO_3). Metal-based catalysts convert up to 5% of sulfur dioxide to sulfur trioxide. Carbon monoxide catalysts will also oxidize up to 50% of sulfur compounds into sulfur trioxide.[40] The sulfur trioxide can then react with the ammonia present in the exhaust gas, forming ammonium salts such as ammonium bisulfate (NH_4HSO_4) and ammonium sulfate [$(NH_4)_2SO_4$].

Catalyst Plugging

Ammonium bisulfate can rapidly corrode any surface on which it deposits. Ammonium bisulfate is also a sticky substance, causing the fouling and plugging of catalyst beds and other equipment, increasing the back pressure on the engine. Ammonium sulfate is not corrosive but it will coat, foul and plug equipment. The coating of ammonium salts on the surfaces reduces the efficiency of any heat transfer equipment. Ammonium bisulfate and ammonium sulfate are also particulate emissions once they exit the stack of the engine. Ammonium salts can be periodically removed by water washing. The removal of ammonium salts helps reduce the rate of corrosion and improve efficiency, but the engine must be shut down for the cleaning, leading to increased costs from down time.

Increases in backpressure on the engine can cause a decrease in the horsepower output and an increase in brake specific fuel consumption. A SCR system will cause a backpressure ranging between 2 and 4 inches of water when it is installed on the engine. This will result in a decrease in output power of 1% in naturally aspirated engines and a 2% decrease in turbocharged engines. The brake specific fuel consumption will increase about 0.5%. Fouling of the catalyst will cause further decreases in power output and increases in Bsfc.

Low Sulfur Fuels

The most effective ways to eliminate problems with sulfur compounds in SCR is to use fuels with little or no sulfur in them or to limit ammonia slip. Natural gas usually has little or no sulfur, but distillate oils usually have some sulfur in them. Some types of natural gas contain hydrogen sulfide which will contribute to ammonium salt formation. Fuels for diesel engines are made with heavier petroleum products and will often have higher sulfur contents. Even the lowest sulfur distillate oils will have some ammonium salt formation from the SCR system.[41]

There are catalysts available for SCR that help prevent the oxidation of sulfur dioxide to sulfur trioxide. These catalysts can be used when a distillate fuel is being used, to help prevent the formation of ammonium salts. Catalysts that contain tungsten trioxide (WO_3) help reduce the formation of sulfur trioxide. Silica based catalysts, which contain titanium dioxide (TiO_2) deposited within silica impregnated with vanadium pentoxide (V_2O_5), perform with a 50% increase in NOx conversion and will reduce the formation of sulfur trioxide.[34] This catalyst can also operate in temperatures which are above ammonium bisulfate formation temperature. Some catalysts that are designed to limit ammonium salt formation are not as efficient at NOx removal; therefore a larger catalyst volume is required. Zeolite catalysts are good at preventing ammonium salt formation since they convert less than 1% of sulfur dioxide to sulfur trioxide.[42] Problems with sulfur trioxide can occur when the sulfur content of the fuel increases.

There are other methods of dealing with sulfur trioxide and the formation of ammonium salts. The system may be modified so that the inlet temperature of the flue gases entering the SCR catalyst will be raised above the ammonium bisulfate formation temperature. Ammonium salts form mostly in the lower temperature regions of the SCR system. Another method of controlling sulfur trioxide formation is to reduce the ammonia slip as much as possible. It should be possible to reduce ammonia slip to between 5 and 3 ppm and possibly even lower.

304.6.4 Ammonia Use

Health Effects

Ammonia is necessary for the chemical reactions in SCR to work. Unfortunately, ammonia is also a hazardous substance. Ammonia is on the Environmental Protection Agency's list of extremely hazardous substances under Title III, Section 302 of the Superfund Amendments and Reauthorization Act of 1986 (SARA). Ammonia is immediately dangerous to life and health (IDLH) at only 500 ppm. It has a time weighted average (TWA) exposure limit (the maximum allowable exposure limit in a 10 hour day in a 40 hour week) of 25 ppm. Ammonia has a pungent, suffocating odor. Exposure to ammonia causes eye, nose, and throat irritation and it will burn the skin.

Ammonia is released from an SCR system because excess ammonia is required for efficient conversion of NOx to nitrogen. Excess ammonia is required because of imperfect distribution of the chemical. In theory, if the ammonia could be perfectly distributed so all the reactants could come into contact, no ammonia would be released, but in the real world this is not possible. This is also analogous to the necessity for excess air required for combustion. Excess air is required since all the oxygen molecules can't find all the fuel molecules to react with during the short period of time of combustion due to imperfect mixing of fuel and air. The molar ratio of nitrogen oxide (NO) to ammonia in the SCR reaction is 1.0 (i.e. 1 ft^3 of ammonia is required to convert 1 ft^3 of NOx), and the molar ratio of ammonia to nitrogen dioxide (NO_2) is two. Over 80% of the NOx compounds in the exhaust are nitrogen oxide, so the SCR system is usually run with a ratio of ammonia to NOx around 1.0. Further increase of the ratio will reduce NOx emissions, but emissions of ammonia will increase.

In an SCR unit it is critical that the ammonia is injected and thoroughly distributed throughout the flue gas stream. This is done with an ammonia injection grid located upstream of the catalyst. Ammonia is drawn out of a storage tank and evaporated with an electrical heated or steam heated vaporizer. The vapor is then mixed with a carrier gas which is usually compressed air or steam. The carrier gas provides the momentum to deliver the gas into the exhaust stream.

Ammonia Slip Levels

The unavoidable release of ammonia out of the engine's exhaust is called ammonia slip. The ammonia slip in a typical SCR system for a reciprocating engine is usually below 10 ppm with a NOx removal efficiency of 90%.[43] In general, the more ammonia that is used the higher the ammonia slip, but the conversion of NOx to nitrogen may increase. As a catalyst ages the ammonia slip increases. Some SCR catalysts react with unreacted ammonia to reduce ammonia slip.

The storage of ammonia is usually considered to be a greater potential hazard than the ammonia slip from the stack. Emitted levels of ammonia slip are far below the odor and health hazard thresholds of the chemical. Since ammonia is water soluble, it doesn't remain very long in the atmosphere.

Ammonia for SCR is stored in a tank and a relatively large amount of storage is required. Accidental release from storage could pose problems to communities surrounding the plant. Aqueous and anhydrous ammonia are the two types of ammonia used for ammonia injection. The aqueous form is favored in that the stored ammonia concentration can be limited and the volatilization rate is reduced, so it is safer. The aqueous form is used in more heavily populated areas. Nationwide, the anhydrous form of ammonia is still used more often. When there is an accidental release of aqueous ammonia with a lower concentration, the ammonia will be released into the air at a slower rate and it will be dispersed faster.

304.6.5 Engine Power Output

Changes in the load and power output of an engine affect the exhaust temperature and the NOx emissions. These changes can cause adverse conditions for the SCR system. Selective catalytic reduction works better at constant loads and power outputs. At low power outputs the exhaust temperature is lower and NOx concentrations are lower, but the NOx removal efficiency of the SCR system is lower. However, the residence time in the catalyst will be higher and the overall NOx emissions will be lower. At higher outputs the exhaust temperature is higher and the NO emissions are higher. In order to keep up with the changes in NOx emissions the flow of ammonia into the SCR system must be varied to maintain the correct ammonia to NOx ratio.

304.6.6 Typical Emissions from SCR

NOx Removal Efficiencies

Table 304.5 illustrates emissions of NOx and ammonia from engines using SCR and natural gas fuel.[44] The table shows the engine manufacturer, horsepower, speed, and percent reduction of NOx and the ammonia slip. Most SCR systems have a NOx removal efficiency of over 80%.

304.6.7 SCR Cost

SCR can work well as a NOx control for reciprocating engines, but it is one of the most expensive. The capital costs of SCR are high and the complexity of the system and the use of ammonia and instrumentation add to it. The Environmental Protection Agency considers cost in determining if a control technology is effective. A control must be cost effective in order to be a Reasonably Available Control Technology (RACT). In one EPA estimate, for example, NOx control was effective if it cost less than $1,300 per ton.[45]

Table 304.5 Emissions Using SCR from Diesel Engines

Manufacturer	Model	Power (hp)	speed (rpm)	Load	NH3 Control	NOx red. %	NH3 Slip
Caterpillar	3408	475	1800	Variable	Load following	90	5
Caterpillar	3412	750	1800	Variable	Load following	95	20
Cummins	KTA 19-G1	560	1800	Variable	Load following	90	20
Caterpillar	3306	270	2100	Constant	Manual	90	30
Cooper	LSV16	2500	700	Variable	Load following	94	20
Caterpillar	3516(3)	2850	1800	Variable	Load following	95	20
Detroit	16V149(2)	2350	1800	Variable	Load following	88	30

304.7 UREA INJECTION

Urea is a chemical that comes in the form of a powder that can also be used in place of ammonia for SCR. The urea is dissolved with water and then injected into the exhaust stream. The urea breaks down to form nitrogen and hydrogen compounds that will react with nitrogen oxide. The temperature range for efficient NOx reduction with urea is higher than the exhaust temperature of most engines, so urea injection is limited to systems where there is supplemental firing applied to the exhaust stream.

304.8 CYANURIC ACID

Cyanuric acid $(HNCO)_3$ is a method of NOx reduction for lean burn engines that does not use a catalyst. Cyanuric acid is a powder that changes into a gaseous isocyanic acid (HNCO) when it comes in contact with heat. The isocyanic acid is then injected in the gas stream after the turbocharger with diesel fuel or propane. The fuel increases the temperature of the exhaust gas to between 1150 and 1450° F, where chemical reactions between nitric oxide and HNCO form diatomic nitrogen, carbon dioxide and water. Since fuel is used, this NOx control is economical for engines used in cogeneration operations where the heat is recovered for other processes.

This control technology is commercially available for lean burn engines between 700 and 13,000 horsepower. It has been used at a power generation/ desalinization plant in California and two other plants outside the state. Cyanuric acid generally can control 80 to 90% of the NOx emissions.[46]

304.9 NON-SELECTIVE CATALYTIC REDUCTION

NOx, CO, HCs Reduction

Non-selective catalytic reduction (NSCR) is another "back end" method of controlling two or more different pollutants at once. A back end control is one where the emissions are reduced after they are formed, and in a "front end" control the pollutant emissions are prevented from forming. The catalysts or "catalytic converters" on automobiles use NSCR. The three way catalysts in automobiles work to eliminate three emissions: NOx, carbon monoxide (CO), and hydrocarbons. In NSCR NOx emissions are reduced to the natural form of atmospheric nitrogen (N_2), carbon monoxide is oxidized to carbon dioxide (CO_2), and hydrocarbons are reacted with oxygen to form carbon dioxide and water. Since more than one pollutant is controlled, the NSCR system uses a "non-selective" catalyst. Unlike NSCR, selective catalytic reduction only controls NOx.

There are two basic steps of chemical reactions that occur in NSCR which includes the oxidation of carbon monoxide and hydrocarbons and the reduction of NOx compounds:

1. $2CO + O_2 \rightarrow 2CO_2$
   $2H_2 + O_2 \rightarrow 2H_2O$
   $HC + O_2 \rightarrow CO_2 + H_2O$

2. $NOx + CO \rightarrow CO_2 + N_2$
   $NOx + H_2 \rightarrow H_2O + N_2$
   $NOx + HC \rightarrow CO_2 + H_2O + N_2$

The step one chemical reactions are used to remove excess oxygen from the exhaust gases, since carbon monoxide and hydrocarbons will tend to react more with oxygen than NOx compounds. Then in the step two reactions, carbon monoxide and hydrocarbons can react with NOx compounds. The oxygen content of the exhaust gas must be kept around 0.5% by volume for efficient reduction of NOx emissions. According to one catalyst vendor, this is accomplished by keeping the air/fuel ratio between 16.95 and 17.05.[47] With different fuels the stoichiometric air/fuel ratio will vary; therefore, the ideal operating air/fuel ratio to give 0.5% exhaust oxygen will be different for different fuels to obtain the best NSCR function. Non-selective catalytic reduction can only be used on rich burn engines because lean burn engines, which operate at higher air/fuel ratios (more air relative to the amount of fuel in the charge), have excessive amounts of oxygen in the exhaust.

Rich Burn Engines Only

The non-selective catalytic reduction system has an oxygen sensor located in the exhaust gas. The sensor helps automatically adjust the air/fuel ratio to maintain the proper amount of oxygen and carbon monoxide for good NOx reduction. If the carbon monoxide and hydrocarbon concentration is too low the NSCR system will not work well. The oxygen sensor is connected to a control system which uses a signal to automatically adjust the actuator on the carburetor of the engine. Systems with manual air/fuel ratio controllers have also been constructed where status lights connected to the oxygen sensor will tell operators when the air/fuel ratio is within the correct range.

A NSCR system may also operate with a dual catalyst bed where the first catalyst is used to reduce NOx and the second catalyst bed oxidizes hydrocarbons and carbon monoxide (Fig. 304.9). Air is injected into the exhaust between the two catalysts. Dual catalyst systems can attain higher NOx reductions and they operate with the engine set slightly richer. However, dual systems are more expensive, and efficiencies of newer conventional NSCR have improved to levels near dual systems.

Limiting Factors

A factor that limits non-selective catalytic reduction as a NOx control is that it can work only with certain types of fuels. Since the catalyst for NSCR is sensitive to poisoning and masking, the fuel burned in the engine must be relatively free of sulfur compounds and other contaminants. Fuel such as

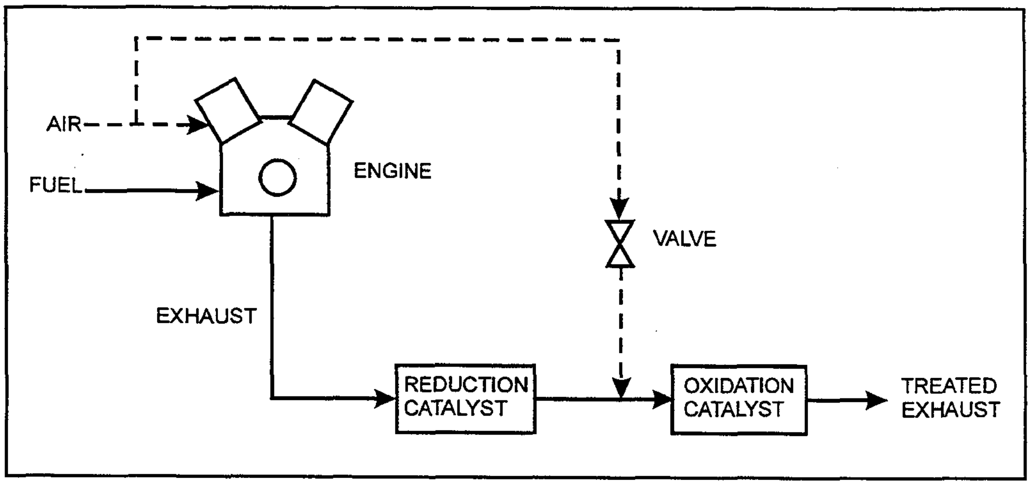

Figure 304.9 Dual Catalyst NSCR System

landfill gas and digester gas usually contain masking and poisoning agents, but it is possible to remove them. On engines that run with cyclic loads the exhaust temperature and NOx and oxygen concentration change. Fuel injected engines with modern electronics can control the air/fuel ratio to keep the oxygen concentration in the exhaust gas within the correct range for efficient NOx removal. Some NSCR designs have been built with other modifications to handle variations in the load. One system uses an enlarged exhaust piping system and a muffler equipped with the catalyst. The larger volume in the exhaust system increases the residence time of the exhaust gases in the catalyst to make up for losses in pollutant removal.

Effective Air/Fuel Ratios

For NSCR to operate properly, an engine is run on the rich side of the best economy air/fuel ratio to maintain the correct exhaust composition. Fuel penalties between 10 and 12% have been observed compared to the best fuel economy setting.[48]

Fuel Sulfur Limits

Natural gas and liquid petroleum gas generally have low amounts of sulfur in them, but fuel gases from oil fields gases and other waste gases may have more. If significant amounts of moisture are also present in fuel gas, it must be controlled to prevent deterioration of the catalyst by sulfuric acid. The sulfur content of fuel gas must generally be limited to 800 ppm by weight. Landfill gases and digester gases contain contaminants that can harm the catalyst.

Another problem with NSCR is that the system increases the back pressure on the engine. In addition, the fuel rich setting for the air/fuel ratio and back

Engine Back-Pressure

pressure reduce power output and increase the brake specific fuel consumption of the engine. The main source of the increased back pressure on the engine is the catalyst. The increase in brake specific fuel consumption, due to back pressure alone, ranged between 0 to 5% according to one manufacturer. Loss in horsepower may be around 1 to 2%.[49]

Masking & Poisoning Agents

Some of the masking agents in the non-selective catalytic reduction catalyst include sulfur, hydrocarbons, calcium, and silica particles. Some of the poisoning agents include phosphorus, lead, and chlorides. Besides being in the fuel of the engine, masking agents may come from the lubricating oil. Masking agents cover the catalyst and prevent pollutant compounds from coming in contact with it so that pollutants can be converted. The effect of poisoning agents on the catalyst are usually irreversible. Poisoning agents will render the catalyst inactive. The effects of masking agents can be removed by cleaning the catalyst. Fine silica particles and other particulate matter can also coat the catalyst.

Catalyst Life

The life of the catalyst is generally guaranteed by manufacturers for at least two to three years. Some vendors will guarantee a NOx reduction efficiency as high as 98%. Since the catalysts contain precious metals, they are expensive, but most manufacturers will give a credit when a new catalyst must be bought.

It is difficult to maintain the proper air/fuel ratio for the best NOx reduction since it is a narrow range. To reduce NOx on one natural gas engine to 2 g/Bhp-hr, for example, requires the air/fuel ratio to be between 15.95 and 16.04:1.[50] Load changes, atmospheric temperature changes, and changes in the fuel heating value can change the air/fuel ratio perceived by the oxygen sensor.

Temperature Range

An important parameter for a NSCR system is the temperature range. The temperature range in the catalyst must generally be between 700° and 1500°F, but for NOx reductions over 90% a narrower temperature range of 800° to 1200°F is required. Since this is also the exhaust temperature of rich burn engines, this works well as a NOx control. NSCR can reduce carbon monoxide emissions by more than 80% and it can reduce hydrocarbon emissions by over 50%. A dual catalyst system may reach 98% reductions in NOx emissions.[51]

The dual catalyst system has a series of two catalyst canisters, where one acts to reduce NOx emissions and the other oxidizes carbon monoxide and hydrocarbons. The dual system has a wider operating window, since it can operate with an engine with a wider variation of air/fuel ratios.

304.9.1 Hybrid System

The hybrid system is an advanced NSCR system where natural gas is injected into the exhaust stream as a reducing agent to reduce NOx. One system injects natural gas in front of the catalyst reactor. In another variation natural gas is injected into an afterburner. The natural gas burns and raises the exhaust temperature to a minimum of 1700°F to maximize the destruction of unburned hydrocarbons. The burner is operated with an excess amount of fuel so that a large amount of carbon monoxide will be produced for the reduction of NOx. The exhaust gases are then cooled in a heat exchanger to 800°F before entering the catalyst. The catalyst reduces NOx compounds into diatomic nitrogen. A second heat exchanger cools the exhaust down to 450°F and air is added before it enters a second catalyst. The second catalyst oxidizes carbon monoxide to carbon dioxide. Cooling the exhaust gases in the second heat exchanger helps prevent the reformation of NOx compounds. This two-catalyst system may also be applied to lean burn engines and it may reduce NOx emissions down to 3 to 4 ppm.[52] The main problem with this system is its high cost.

304.9.2 NSCR Catalyst

The materials that have often been used in three way catalytic converters are platinum, palladium and rhodium. Platinum or palladium oxidize carbon monoxide into carbon dioxide and oxidize hydrocarbons into carbon dioxide and water. Rhodium is used to reduce NOx compounds to diatomic nitrogen (N_2) which is its normal form in the atmosphere. The catalyst is usually in the form of a ceramic mesh which may be a honeycomb structure, or aluminum oxide pellets coated with the catalyst. The ceramic mesh type are also called "monolith" catalytic converters. The mesh type is more durable and creates less back pressure on the engine. The efficiency of the catalyst in controlling the pollutants is over 90% for NOx, 80% for CO and over 50% for hydrocarbons. Three way catalysts are not used on diesel engines because the oxygen in the exhaust interferes with the reduction of NOx.

Catalyst Life

The length of time the catalyst in a catalytic converter may last varies. There is disagreement among vendors concerning this, but the existence of contaminants in the fuel, maintenance (i.e., catalyst cleaning), and other factors affect the life of the catalyst. Some vendors claim that the catalyst may even last as long as the engine. Some substances that shorten the catalyst life include hydrogen sulfide (H_2S), silicone, and oil additives.

Engine backfire and exhaust gas pulsation can damage the catalyst. The exhaust system may be equipped with a backfire relief valve to prevent damage. Putting the catalyst after the muffler helps protect the catalytic converter, but the exhaust gas temperature will be reduced substantially, resulting in a lower conversion efficiency. On the other hand, if the catalyst is before the muffler the temperatures will be high for conversion of pollutants but it will not be protected from destructive pulsation. In some catalytic converters the unit may serve both as a muffler or silencer and a pollutant control device.

304.10 LOW EMISSION COMBUSTION

Use Very Lean Air/Fuel Ratios

Low emission combustion involves using very lean air/fuel mixtures to reduce emissions. Looking at the Figure 302.1, it can be seen that with very lean mixtures, emissions are lowered. In order to reach these lean air mixtures more air is put into the engine. For rich burn engines, which operate near stoichiometric, the amount of air entering the engine is nearly doubled. This is done by adding a turbocharger and intercooler, or an aftercooler, to a naturally aspirated engine, or replacing an existing turbocharger and intercooler/ aftercooler with one with a larger capacity. The air intake, filtration system, carburetors, and exhaust system also have to be replaced, to handle the larger air flows. The two main engine design modifications used in low emission combustion include an open chamber and a precombustion chamber.

304.10.1 Open Combustion Chamber

The open combustion chamber design is a modification that is usually done on relatively small-sized bore engines. In these engines the combustion chamber is modified so the air and fuel charge will have a swirling motion to increase turbulence. This helps mix the fuel and air so that combustion can occur much more easily at lean air/fuel ratios.

304.10.2 Precombustion Chamber (PCC)

In engines with larger bore sizes, an open chamber design will not work well enough to ignite a very lean mixture. Therefore a precombustion chamber may be used. A precombustion chamber is a small chamber connected to the main combustion chamber or cylinder of the engine (Fig. 304.10). The precombustion chamber has 5 to 10% of the volume of the main combustion chamber.[53] A rich air/fuel mixture that is easy to ignite is put into the precombustion chamber. Combustion can then propagate through the rest of the

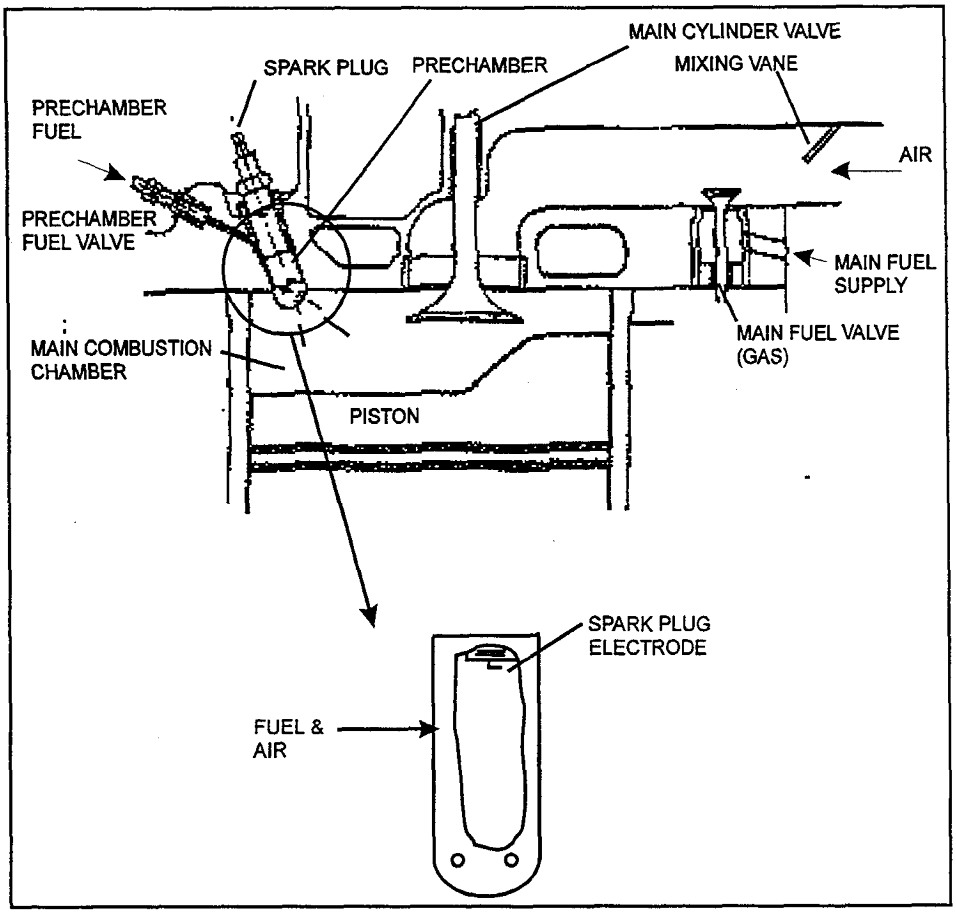

Figure 304.10 Prechamber for a Gas Engine

cylinder, burning the very lean air/fuel mixture. The dilution effect of the excess air in the cylinder reduces combustion temperatures and NOx formation.

In spark ignition engines the prechamber sits just below the spark plug so the spark can ignite the rich mixture in the prechamber.. The prechamber design can also be used in compression ignition engines and dual fuel engines. As with typical CI engines there is no spark plug, but an injector is used to inject fuel into the prechamber. Combustion in the prechamber starts by the heat of compression. The fuel efficiency of compression ignition engines with a prechamber is lower than those without the retrofit. Retarding the timing of CI engines with prechambers is also less effective for NOx reductions.

Combustion products from the precombustion chamber have a very high velocity and create a torch-like effect in the main combustion chamber. The burning from the precombustion chamber also helps improve mixing in the main combustion chamber. The air/fuel ratio in the precombustion chamber design can be much leaner than the open chamber design.

Other Engine Modification Requirements

Manufacturers have various names for this type of modification, including torch ignition, jet cell, clean burn and others. Using a precombustion chamber modification requires other changes to the engine including replacing intake manifolds, cylinder heads, pistons, and the ignition system. Kits for the modifications are available from manufacturers for spark ignition engines. Kits for modifying diesel engines are generally not available.

Some factors that are affected by low emission combustion are the duty cycle and fuel delivery. The duty cycle is the load on the engine; the load that an engine can handle may be reduced by using low emission combustion. Different engines may have different reductions in the load capacity. According to one manufacturer, turbocharged engines can handle load increases up to 50% of the rated load, but naturally aspirated engines can handle 100% of the rated load. With these load increases, it takes a turbocharged engine 7.0 seconds to recover to rated speed and it takes a naturally aspirated engine 3.5 seconds to recover.[54] Engines that are used for applications that have substantial changes in load may not be able to use low emission combustion as a control. The fuel delivery pressure, especially for turbocharged engines running gaseous fuels, may have to be higher. The fuel gas pressure is raised by adding a fuel gas booster.

NOx Reduction Levels

Most spark ignition engines can attain NOx emissions below 130 ppm or greater than 80% NOx reduction with a prechamber. Diesel engines, which generally have uncontrolled NOx emissions between 900 and 1500 ppm, have emission reductions down to 400 to 800 ppm.[55] Prechamber dual fuel engines can reach NOx levels below 90 ppm.

304.11 THERMAL BARRIER COATING

Thermal barrier coating involves applying a ceramic barrier to the surfaces inside the combustion chamber, including the valves, tops of the pistons, and cylinder heads. Modern thermal barrier coatings are applied with a metallic bond coat and a ceramic top coat by a robotic thermal spray process. The coating protects the parts from high temperature corrosion and thermal shock, reduces thermal fatigue, reduces the temperature of parts, and converts more heat into useful energy.

Problems with Thermal Barrier Coatings

A problem with early thermal barrier coating technology was that the brittleness of the ceramic coatings made them unable to withstand the thermal shocks and compressive loads of the engine. The coatings must also handle contaminants such as sodium, vanadium, and sulfur, found in low grade fuels. The thickness of the coating is critical, since uneven heating of the surface can cause the coating to degrade.

In diesel engines using thermal barrier coatings, since more heat is kept in the cylinder, there is a reduction in the delay between the start of fuel injection and ignition of the fuel. This increases the time period for combustion, resulting in lower peak temperatures and more complete combustion. Emissions of hydrocarbons, carbon monoxide, and particulates are reduced, but the effect on NOx emissions is small. On the other hand, other NOx controls (such as ignition retard) can be used with a decrease in lost fuel consumption and power output.

Thermal barrier coatings also work to increase engine life, reduce engine noise and increase cold start reliability at cold temperatures. One study showed that engine life was increased 20%, that power output was increased 10% and emissions were reduced 20 to 50%.

Thermal barrier coatings are available with aftermarket parts that can be installed when an engine is rebuilt. It is also available from a limited number of engine manufacturers for new engines, including Detroit Diesel, Caterpillar, Mermaid Marine, and Cummins.[56]

304.12 COMPRESSION IGNITION FUEL INJECTOR MODIFICATION

Adding electrically controlled fuel injectors can add flexibility to the ignition timing of the engine. With electronic injection, an engine can be retarded more under certain modes and less under other modes, for optimum NOx reduction with the least adverse effects on performance.

Fuel injectors with finer, more uniform spray patterns help reduce emissions of hydrocarbons, carbon monoxide and particulates. NOx emissions may also be lowered a small amount. Higher injection pressures help make a finer, more uniform spray of fuel and the injection of fuel takes less time. With a shorter injection time the injection can start later and end earlier. This has the same effect as retarding injection timing and results in lower NOx emissions. The engine efficiency is also increased.

304.13 INTERCOOLERS AND AFTERCOOLERS

Superchargers and turbochargers increase the temperature of the air entering an engine from the heat of compression. The higher air temperatures increase combustion temperatures and NOx formation. Intercoolers or aftercoolers are heat exchangers used to cool the air entering the engine, to reduce NOx.

NOx Reductions

Reductions in NOx emissions from cooling the entering air may range between 3 to 35%.

The air can be cooled with water from the radiator, water from another source outside the engine, or atmospheric air. The inlet air will be cooled more if the ambient air or a separate source of water is used for the cooling. Without any cooling, the air entering a diesel engine may rise to a temperature of 350° F, and an intercooler using radiator water may cool it to 210° F. An intercooler using ambient air or an outside source of water may cool the inlet air to 90° F. A large industrial stationary engine may operate with a dual core radiator where the main or jacket water core operates at a temperature as low as 180°F and a second core cools water for auxiliary systems. The main auxiliary system is usually the intercooler and it may operate at a temperature as low as 130°F.

Other Benefits

Besides reducing NOx emissions, cooling the inlet air makes it denser, so the mass of the air entering the engine is increased and the power is increased. Since the increase in power is attained with little energy taken from the engine, the intercooler also helps improve fuel efficiency.

304.14 EXHAUST GAS RECIRCULATION (EGR)

Exhaust gas recirculation (EGR) involves recirculating some of the exhaust gases from the exhaust manifold back into the engine's intake manifold. The exhaust gas has a low oxygen content and acts as a heat sink. This lowers combustion temperatures and results in less NOx formation. The operation of an engine may also be adjusted so that more exhaust remains in the cylinder after the exhaust stroke. This tends to have the same effect as a typical EGR system. NOx emissions may be reduced up to 30% from exhaust gas recirculation.

Diesel Engines

Because diesel engines operate at high temperatures and pressures, they are a significant source of NOx emissions, especially at very lean air/fuel ratios, e.g., idle speeds. Diluting the intake air (high oxygen) with exhaust gases (low oxygen) reduces the oxygen available for combustion, thereby lowering combustion temperature and NOx emissions. The principal is identical to EGR for gasoline engines; however, because of the diesel engine's high compression operation, the EGR valve is actuated with the aid of a vacuum pump. The strength of the signal from the vacuum pump to the EGR valve is controlled by a regulator valve, with the signal being highest at idle, and decreasing to zero at full engine throttle. The EGR valve, then, is wide open at idle speeds and closed at full throttle.

Some diesel EGR systems include an EGR controller which receives input from the engine speed sensor, an injection pump control sensor and a coolant thermoswitch, and based on this information, sends varying signals to the vacuum regulator valve which then actuates and controls the EGR valve. For some engines and applications, an exhaust pressure regulator valve is activated at idle/low load conditions to increase exhaust backpressure, increasing exhaust gas flow through the EGR valve.

Disadvantages of EGR

A disadvantage of EGR is that it lowers the power output and efficiency of an engine. In larger-sized stationary spark ignition engines the exhaust gases must be cooled and filtered. A complex control system controlling the amount of recirculated exhaust is also required. EGR tends to foul the intake system, increasing engine wear and engine deposits in compression ignition engines. Particulates from the engine exhaust may clog the ducting and controls leading to the intake manifold.

304.15 EGR SHEATHING

EGR sheathing is a NOx control that is still in the development stage. It involves sending a column of air into the combustion chamber. The air envelopes a column of returning exhaust gas. The column deflects the flame front and it blends with the air/fuel mixture, creating the best burn condition. EGR sheathing operates somewhat like a combination of prestratified charge and exhaust gas recirculation.

Source tests on rich burn engines using EGR sheathing resulted in NOx reductions as high as 96% when compared to uncontrolled NOx emissions. Varying the air injection rate has a larger effect on emissions than varying the EGR rate. One of the engines tested with EGR sheathing showed a 13% increase in fuel consumption and also had only a 13% decrease (7.3 g/hp-hr to 6.4 g/hp-hr) in NOx emissions when used only with PSC.[57]

304.16 AIR INJECTION

Reciprocating engines, like all other processes, do not operate with 100% efficiency. Losses in efficiency can be attributed, in part, to friction and associated waste heat energy, and less than perfect conversion of chemical energy into mechanical energy. These losses begin with the combustion process. In an ideal engine liquid fuel would be perfectly atomized into infinitely small droplets which are then perfectly mixed with stoichiometric quantities of air to complete combustion. In a real engine, however, the combustion process is less than perfect. A small amount of unburned fuel remains in the combustion chamber at the end of the combustion cycle and is subsequently exhausted along with the products of combustion. These exhaust gases are, therefore, a source of hydrocarbon and carbon monoxide emissions.

If the combustion process could be completed after the gases leave the combustion chamber, these emissions could be averted. If there is sufficient oxygen remaining in the exhaust gases, then heat in the exhaust system could complete combustion, provided there is adequate mixing and time. These constitute "The Three T's" of combustion, namely, time, temperature and turbulence. The Three T's are provided by a typical exhaust system, but post combustion chamber burning is limited because the oxygen present in the exhaust gases is insufficient. Air injection systems provide the added oxygen needed to complete the combustion process.

HC and CO Reductions

There are two basic types of air injection systems: the air pump system, which utilizes a pump to inject air into the exhaust system; and the pulse air system, which uses the exhaust system's vacuum pulses to draw air into the exhaust manifold. Both of these air injection systems provide the added oxygen needed to complete post combustion chamber fuel burning, thereby reducing HC and CO emissions.

304.16.1 Air Pump System

In the air pump system, a belt-driven pump pressurizes air and injects it at or near the exhaust manifold. This added supply of oxygen mixes with any residual fuel remaining in the combustion chamber exhaust. The heat from the exhaust manifold is sufficient to ignite the air/fuel mixture and burn the fuel that was not burned in the combustion chamber.

Some air pump systems inject additional air into the catalytic converter upon startup. The catalytic converter does not operate effectively until it heats up, but with the extra fuel-rich operation at startup, the fuel-rich exhaust can be combusted given enough oxygen. The air pump system supplies the necessary oxygen, causing the fuel to burn, which heats up the catalyst for effective emissions control sooner than if that air was not supplied.

A diverter valve and a one-way check valve are usually supplied with the air pump system to prevent backfires during rapid deceleration, and to allow air into the manifold while preventing exhaust from flowing into the air injection system.

304.16.2 Pulse Air System

The pulse air system uses the exhaust system's vacuum pulses to draw air into the exhaust manifold, eliminating the need for a pump and associated equipment. When exhaust valves are opened, exhaust pressure is high, but when the exhaust valves are closed again, the gases flowing out of the exhaust system cause a vacuum to form. Pulse air check valves are attached to the exhaust system so that during the brief periods of vacuum, air can be drawn into the pulse air system and injected into the exhaust manifold.

304.17 EVAPORATIVE EMISSIONS CONTROL

Evaporative emissions can be substantial for liquid-fueled engines, especially gasoline-powered engines. Gasoline is volatile and evaporates quickly at normal temperatures and pressures. The fuel tank and carburetor float bowl are full of this volatile fuel. As ambient and operating temperatures rise, more fuel is evaporated. For safety and operational reasons, the tank and float bowl must be ventilated. Historically, they were vented directly to the atmosphere, where the emitted hydrocarbons added to air pollution. When automotive emissions were recognized to be a major source of man-made air pollution, it was estimated that approximately 20% of automotive hydrocarbon emissions came from fuel system/tank/float bowl vents.

Venting automotive fuel vapors directly to the atmosphere has been prohibited in California since 1970. Since then, evaporative emissions control systems have been developed to prevent venting of emissions to the atmosphere while allowing for proper fuel system ventilation. Most evaporative emissions are generated by gasoline-powered engines when a warm engine is turned off. To avoid these emissions, the fuel vapors must be held and stored until the engine is operating again, at which time they can be burned. This means that evaporative emissions are most significant for gasoline-powered sources which operate intermittently. However, most intermittent-use IC engines, such as emergency generators, fire fighting and portable equipment, are not gasoline powered; therefore, evaporative emissions controls are not further addressed in this manual.

304.18 OTHER EMISSION CONTROL METHODS

Some other emission control methods include water injection, water fuel emulsions, power derate, and the use of alternative fuels. Some of these methods, such as water injection and water fuel emulsions, are used to control emissions from other processes.

Water Injection

Water injection has been used extensively as a NOx control for gas turbines. It reduces emissions by quenching the flame in the combustion chamber, reducing the temperature and therefore lowering NOx production. Water injection is mostly associated with diesel engines; to reduce emissions, water may be injected into the intake manifold of the engine. NOx emissions reductions of up to 50% have been attained with water injection.

Problems with water injection have been encountered, but its use is increasing, especially in large ship engines. Water can dilute the engine's oil and break down the oil films, increasing engine wear. High temperature in the cylinders help keep water in the vapor state to prevent dilution of oil in the cylinders. The water can also cause the corrosion of engine parts and it must be purified so that deposits will not accumulate in the engine.[58]

One manufacturer has developed an engine that uses water injection. This engine uses a stratified fuel/water injection system where pulses of fuel and water are injected. A pulse of pure fuel is injected first, followed by a pulse of pure water. With a water/fuel ratio of 0.5, NOx emission reductions of 60% are attainable.[59]

Water-In-Oil Emulsion Injection

Water-in-oil emulsion injection is a method used to reduce NOx emissions in oil-fired gas turbines by emulsifying water in fuel oil before it is injected into the combustor. This system reduces NOx by the same principles of water or steam injection, but with greater emission reduction.

Engine Derating

Engine "derate" is reducing the power output of the engine by reducing the fuel flow. This lowers the combustion temperatures and pressures, lowering NOx emissions. Emission tests with this technique have shown NOx reduction for spark ignition engines between 0.2 to 6.2%.[60] For compression ignition engines, emissions may actually increase at reduced power levels.

Alternative Fuels

Using other fuels with lower flame temperatures is another method of reducing NOx emissions. The main problem with using alternative fuels is that they are generally not economical. Methanol has a flame temperature of 3500°F compared to the 3660°F flame temperature for natural gas.[61] Distillate oils have even higher flame temperatures than natural gas. Since NOx emissions are highly dependent on the combustion temperature, the lower combustion temperatures from methanol will produce less NOx.

The NOx emissions from using methanol depend heavily on the type of engine. Engines converted from burning natural gas generally have about a 30% reduction in NOx, and engines converted from burning diesel have a maximum of about 80% reduction in NOx.

Converting gaseous and gasoline fueled engines to methanol requires engine modifications. Converting diesel engines to methanol requires much more extensive modifications. Some of the changes include oversized injectors and pumps, and the addition of cetane improvers to the fuel.

Coal gas is gaseous fuel derived from coal that has a flame temperature below that of natural gas. The costs of coal gasification make coal gas unattractive. Coal-water slurries have also been test fired in reciprocating engines, resulting in lower NOx emissions.

304.19 COMPUTER CONTROLLED SYSTEMS

This section begins by addressing computer control systems pioneered by and developed within the automotive industry. These systems affect both engine performance and emissions for most modern vehicles. Some of the systems described in this section may appear to have little or no application to stationary sources (e.g., air conditioning sensor, torque converter clutch solenoid); however, it is important to understand the extent to which vehicle manufacturers have engineered these systems, through monitoring and controlling, to reduce emissions. The first subsection provides a brief overview of these systems in terms of their development and use within the automotive industry.

Most of these technologies are also directly applicable to stationary reciprocating engine emissions control and are utilized, to some extent, for this purpose. The second subsection provides a brief overview of the electronic sensing and computer controlled systems applied to some modern stationary reciprocating engines.

304.19.1 Automotive Computer Controlled Systems

Electronic Engine Control

Almost all vehicles manufactured today use an Electronic Engine Control System (EEC). The heart (center) of the EEC system is a computer called the Powertrain Control Module (PCM). The PCM has made it possible to maintain good driveability while increasing fuel economy and decreasing vehicle emissions. There are three main components to the EEC system: The PCM, Input Devices and Output Devices.

Powertrain Control Module

The PCM is a microcomputer much like a home or small business computer. It is a sealed unit usually located inside the vehicle to protect it from the elements. The PCM has four basic functions: data input, information processing, storage and output commands. It operates in two modes: closed loop and open loop. The PCM is powered up with battery voltage but supplies the sensors with a 5 volt reference voltage. The 5 volt signal is used because it remains constant and is not subject to the variation of the vehicle's 12 volt charging system. The PCM is linked to sensors and actuators called Input Devices and Output Devices through a dedicated wiring harness. The following narrative will discuss the PCM's four basic functions, closed loop operation, and the input and output devices.

Various information is input to the PCM through sensors mounted throughout the engine and vehicle. The PCM compares the signals to preprogram information and makes a decision for various output commands.

The PCM has its own preprogrammed set of operating instructions in memory. This includes information about the vehicle's engine specifications, transmission, vehicle weight, air conditioning and other accessories. This data is stored in the PCM's read only memory (ROM) and provides the PCM with its calibration ability, using these calibration values to solve equations and make decisions. The PCM also stores information in random access memory (RAM). This information, also referred to as "volatile" memory, is used during vehicle operation and is lost whenever the ignition key is turned off. Information is also stored in keep alive memory (KAM), also referred to as non-volatile memory. The information stored in KAM is not lost when the key is turned off. The PCM stores the constantly changing data supplied by the sensors and has the ability to learn, called adaptive learning. The PCM monitors important circuits whenever the ignition switch is on or the engine is running. If a particular circuit is open, grounded or out of range, it will cause the PCM to store an associated fault "trouble" code and turn on the Malfunction Indicator Lamp (MIL) on the instrument panel. The MIL remains on as long as the fault causing the problem is present.

After the PCM receives the data, processes it, and matches it to the information programmed in ROM, the PCM then sends output commands to various actuators. These actuators are electromechanical devices which control fuel metering, ignition timing, emission control systems, and other engine functions.

When the engine is at normal operating temperature, after a short period of time has elapsed and other basic parameters are met, the engine will assume a closed-loop operation. Closed-loop assures that the engine is operating within the ideal air/fuel ratio emission window called stoichiometric operation (about 14.7 to 1 air/fuel ratio). The information stored in the PCM is used to control the engine throughout all operating conditions. These signals are used to activate solenoids, relays, switches, or stepper motors. Opened-loop means that the engine has received a signal (or an unacceptable signal) from one or more of its sensors indicating it's not ready or able to operate within the stoichiometric window.

Input Devices

Input devices are the components, generally known as sensors, that transmit signals to the PCM describing the state, temperature, position, or operating status of the system or part they monitor. There are several input devices. The most common are:

- Engine Speed and Ignition Control Module,
- Throttle Position Sensor,
- Engine Coolant Temperature Sensor,
- Intake Air Temperature Sensor,
- Oxygen Sensor,
- Vehicle Speed Sensor,
- Gear Selector and Transmission Temperature/Pressure Sensors,
- Inferred Mileage Sensor,

- Barometric Pressure Sensor,
- Manifold Absolute Pressure Sensor,
- Mass Air Flow Sensor,
- Air Conditioning Sensor,
- Engine Knock Sensor,
- Exhaust Gas Recirculation Position and Pressure Sensor.

Engine Speed Sensors

The engine speed sensors transmit the engine RPM, crankshaft position, and camshaft position signal through devices such as a magnetic pickup, Hall Effect switch, and optical sensor or a variable resistance sensor. The signal is used for RPM and crankshaft position so that proper spark timing and injection timing (fuel delivery) can be calculated.

Ignition Control Module

The ignition control module (ICM) processes a signal generated by the PCM to regulate the opening and closing of the primary circuit to control dwell and electronic spark timing.

Throttle Position Sensor

The throttle position sensor (TP) is a potentiometer that sends an analog variable low DC voltage signal. It is mounted so that it moves in proportion to the throttle plate. The TP sensor monitors both motion and position. The signal voltage is low at closed throttle and gradually increases to about 4.75 volts at wide open throttle. The PCM uses the TP sensor input for fuel delivery and ignition timing control. As the throttle opens the PCM receives a higher voltage input and then increases the fuel injector pulse width for more fuel delivery. The PCM may also use TP input to advance the ignition timing based on PCM calibration tables.

Engine Coolant Temperature

The engine coolant temperature (ECT) sensor is a thermistor type solid state variable resistor that usually is a negative temperature coefficient (NTC) which decreases resistance as temperature increases. The ECT is used in the control of fuel delivery, ignition timing, idle speed, cooling fan operation, torque converter clutch operation and other emission control devices.

Intake Air Temperature

The intake air temperature (IAT) sensor is a NTC thermistor. The thermistor decreases resistance as temperature increases. The operation of this circuit is very similar to ECT.

Oxygen Sensor

The oxygen (O_2) sensor is a galvanic battery and most are made of zirconium dioxide (zirconia). The signal voltage range is usually from 0.1 to 0.9 volts; that is directly proportional to the difference between the oxygen content of the atmosphere and the oxygen content of the engine's exhaust. In lean conditions, with high oxygen content in the exhaust, there is somewhat less difference between the oxygen in the air and the oxygen in the exhaust and the sensor will produce a lower voltage. In rich conditions, with less oxygen in the exhaust, the O_2 sensor generates a high voltage which transmits a rich condition signal to the PCM. During stoichiometric operation the sensor continually switches between high and low voltage, signaling the PCM to maintain the ideal air/fuel ratio.

Vehicle Speed Sensor

The vehicle speed sensor (VSS) transmits a signal in proportion to vehicle speed. The VSS can be a pickup coil, optical sensor, or a magnetic reed switch. The VSS can be mounted in the speedometer, transmission/transaxle assembly. The VSS data is used by the PCM to control the cooling fan, canister purge, torque converter clutch lockup, cruise control operation and high speed fuel cutoff.

Transmission Sensors

The gear selector sensor transmits a signal to inform the PCM that the transmission is in gear, park or neutral position. The transmission temperature/ pressure sensors are either thermistors or pressure switches that the PCM uses for a variety of outputs such as which gear is engaged, when to apply the torque converter clutch operation, hot mode determination, shift quality, EGR valve operation and spark timing.

The inferred mileage sensor accounts for engine on-time. When the PCM receives a change in signal over a period of time, from this sensor, the PCM will change its internal calibration to account for engine wear.

Barometric Pressure Sensor

The barometric pressure sensor (BARO) is a piezoresistive crystal that converts changes in atmospheric pressure to an electrical signal and sends the signal to the PCM. The signal is proportional to atmospheric pressure. The PCM uses the BARO sensor information input primarily for fuel delivery and ignition timing control.

Manifold Absolute Pressure

The manifold absolute pressure (MAP) sensor is also a piezoresistive crystal that sends an analog voltage signal to the PCM that is proportional to intake manifold air pressure (or vacuum). The PCM uses the MAP sensor information for fuel delivery and ignition timing control.

Mass Air Flow Sensor

The mass air flow sensor (MAF) is located between the air cleaner and throttle body. Its sensor is a heated wire or film element that is maintained at a known temperature higher than ambient. The signal is proportional to the weight (molecular mass) of the air entering the engine (a cubic foot of cool air contains more mass than a cubic foot of warm air). By measuring the mass of the air entering the engine, the PCM can more accurately gauge the amount of fuel necessary for efficient combustion. The PCM uses the MAF sensor readings for fuel delivery, spark timing, torque converter clutch activation and EGR operation.

The air conditioning (A/C) sensors monitor the air conditioning operation for on/off activity and pressure. When the PCM receives an A/C request it uses this signal to determine control of the A/C compressor clutch operation, engine idle speed and coolant fan operation. An A/C sensor may also monitor high side A/C pressure and/or how much load the A/C system places on the engine.

Engine Knock Sensor

The engine knock (KS) sensor is a piezoelectric device that measures vibration and converts the vibration into an electrical signal. The PCM uses this signal to retard ignition timing a fixed number of degrees, or in increments, depending on how the computer is programmed, until the engine knock ceases. When the knock (pinging) is no longer detected by the sensor, the PCM returns the ignition timing to normal. Engine knock can increase emissions and damage internal engine parts. See Section 205.9.1 for more information about preignition and engine knocking.

Exhaust Gas Sensors

The exhaust gas recirculation (EGR) valve position sensor is a linear, sliding contact potentiometer mounted on top of the EGR and connected to the valve stem. The EGR position sensor operates very similarly to the throttle position sensor. The sensor monitors valve stem movement and therefore EGR flow rate. The PCM uses EGR valve position information for accurate control of the EGR vacuum regulated solenoid (an output device). On some applications, exhaust pressure sensors are used to inform the PCM about the amount of exhaust gas the EGR valve allows into the intake manifold. This type does not use the valve stem position sensor but uses two sensors: a pressure feedback sensor and differential pressure feedback sensor. See Section 304.14 for more information regarding the operation of the exhaust gas recirculation system.

Output Devices

Output devices are actuators that are controlled by the PCM. After processing information received from the input sensors, the PCM matches that information with its memory tables, makes a decision and transmits the signals to an output actuator. Some of the types of actuators used in computerized engine control systems are solenoids, relays, and stepper motors. Actuators include:

- Fuel Injectors,
- Fuel Pump Relay,

- Canister Purge Solenoid,
- Mixture Control Solenoid,
- Idle Air Control Valve,
- Torque Converter Clutch.

Fuel Injector Solenoid

Fuel injectors are output devices because they generally use electrical solenoids mounted in the throttle body or in the intake manifold. When the injector(s) receives a signal from the PCM, the solenoid opens a small orifice, allowing fuel to flow. The amount of time that the PCM turns on the injector circuit is measured in thousandths of a second (milliseconds). The longer the amount of time, the more fuel is delivered to the cylinder. See Section 205.8.2 for more information regarding fuel injection.

Fuel Pump Relay

The fuel pump relay is another example of an actuator. Most systems use an electric fuel pump to supply fuel to the injectors. The power is generally supplied to the relay through a fused circuit regulated by the PCM. If the PCM does not see a distributor or crank signal pulse, the relay will not be energized and fuel will shut off. The relay may also receive a shut off signal if the PCM senses excessive RPM or in the case of a vehicle roll-over.

Canister Purge Solenoid

The vapor canister collects fuel vapors from the fuel tank, and from the carburetor on carburetor equipped engines. Because the vapor canister can be an additional source of unburned fuel, the computer limits purging during cold engine operation to reduce cold start emissions. The computer may also limit canister purge if it detects a rich exhaust condition, and limit canister purge during wide open throttle or during restarts. The engine computer monitors engine coolant temperature, engine speed (RPM) and throttle position, then determines when to purge the canister via a solenoid.

Mixture Control Solenoid

The mixture control solenoid is used on some computer controlled carburetor engines to control air/fuel mixture. Early feedback carburetors used a vacuum diaphragm to lower or raise a metering rod, thereby changing the mixture. The vacuum to the diaphragm is controlled by a vacuum regulator which is controlled by the computer. A duty cycle solenoid is used to control the amount of vacuum sent to the diaphragm, the rod is pulled far from its seat and a large amount of fuel is allowed to flow through the carburetor's main jet. Likewise, when the vacuum is high, the rod is close to its seat and allows for a lean mixture.

Another type of mixture control device uses an electric mixture control solenoid controlled by the computer and attached to the carburetor. Air/fuel ratios are varied by the length of time the solenoid is activated during each on-off cycle. Because the solenoid is in the full fuel delivery position when it is deactivated, less on-time will cause the mixture to enrich. The period of time that the solenoid's circuit is completed is referred to as its "dwell" time.

Idle Air Control Valve

The idle air control (IAC) valve controls engine idle speed and prevents stalls due to changes in engine load. The IAC is usually a reversible DC stepper motor that moves in increments, or steps. The motor moves a shaft back and forth to operate a conical valve. When the conical valve is moved back, more air can bypass the throttle plates and enter the engine, increasing the idle speed. As the conical valve moves inward, the idle speed decreases. Some computerized engine systems use a solenoid operated valve, instead of a stepper motor, to control idle speed. The PCM will calculate the proper position of the IAC valve during idle or deceleration based upon battery voltage, coolant, engine load, vehicle speed, and engine rpm.

Torque Converter Clutch

The torque converter clutch (TCC) solenoid valve is a PCM controlled valve inside the transmission. When the coolant temperature, vehicle speed, throttle position, engine load, and gear range are correct, the PCM energizes the TCC driver circuit. The TCC solenoid then engages the torque converter clutch by redirecting hydraulic pressure in the transmission or transaxle. For the torque converter clutch to operate properly, the engine coolant temperature must reach normal operating temperature and the vehicle must be at a steady state cruise speed, usually above 40 miles per hour.

304.19.2 Stationary Engine Electronics and Computer Controlled Systems

This section presents information currently available on electronic sensing and computer controlled systems for some stationary reciprocating engines. Several engine manufacturers were contacted; however, only Caterpillar® and to a lesser extent, Superior®, reported widespread application of electronics and computer controlled systems on their modern stationary engines. A summary of relevant information available in these two manufacturers' engine specification catalogues and product information brochures follows.

Gas Engines

Superior® produces gas engines with matched compressors in the 500 to 3200 brake-horsepower range. Superior® 1700 and 2400 series gas engines are

Electronic Control

equipped with the patented "CleanBurn™ III" electronic control system. This system continuously monitors engine operating performance and adjusts the air/fuel ratio to optimum emissions and fuel consumption levels. It offers higher reliability than conventional control devices because information is based on real time measurement as opposed to some preset configuration. Critical engine temperatures and pressures are constantly being measured. It adjusts not only for engine speed and load variations, but also for changes in ambient conditions and fuel quality. Additionally, an operator interface panel is offered which gives the operator simple and direct access to engine control functions, including: automatic start sequencing, safety alarms and shutdowns, fuel sensing, speed, ignition timing, and more.

CleanBurn™ III electronic control features include:

- Air/Fuel control based on real time measurement,
- Fuel quality compensation,
- Variable ignition timing based on ambient conditions, engine speed, engine load, fuel,
- Real time closed-loop starting control,
- Engine speed governing,
- Auto, local and remote control,
- Modular design.

Input Devices

Input devices, which monitor engine operating parameters and send the data to the control unit, include:

- Temperatures
  - Ambient
  - Air manifold
  - Fuel
  - Jacket water
  - Intercooler water
  - Lube oil
  - Pre-turbine
  - Individual cylinder
- Pressures
  - Barometric
  - Main fuel
  - Pilot fuel
  - Air manifold

- Oil
- Jacket water
- Intercooler water
- Flow Measurement
  - Main fuel
  - Pilot fuel
  - Air
- Engine speed
- Battery voltage

Based on data received from the input devices and sensors, and from the operator interface, the CleanBurn™ III microprocessor control unit continuously adjusts the following controls:

- Main Fuel Control
- Pilot Fuel Control
- Ignition Timing
- Speed Control
- Start Sequencing Control
- Safety Alarm and Shutdown System

During the past decade, advanced designs have a played a role in improving the operation of diesel engines. Meeting the need for greater fuel economy and better performance, along with new standards mandating lower exhaust emissions, required more sophisticated engine controls and fuel systems. To meet these demands, Caterpillar, as well as other engine manufacturers, have developed fully integrated electronically controlled engines.

Electronic Unit Injectors

The 3500 series Caterpillar diesel engines are used for electric power generation and marine applications. They are available with an electronics package option. This option removes the standard mechanical unit injection fuel system and replaces it with the ADEM™ II control and monitoring system with electronic unit injectors (EUI).

The EUI option provides the following benefits to the operator:

- Monitors, diagnoses and communicates problems locally or globally;
- Predicts problems before they occur and protects engine from harm;

- Lowest fuel consumption in the industry, allowing lower total operating cost;
- Variable timing--optimizes performance across all loads and speeds;
- Enhanced performance at low operating speeds, providing rated power across a wide operating range;
- Virtually smokeless engine exhaust, without add-on emission control systems;
- Ability to program shutdown and alarm set points;
- Interface with customer communication module.

The electronic unit injector is mechanically actuated and electronically controlled. It combines an electronic actuator, pump assembly, and nozzle into a single compact unit. It provides fuel injection at 20 percent higher pressure than previous mechanical unit injectors and provides much more precise metering and timing of fuel delivery for superior performance. The EUI delivers fuel to each cylinder's combustion chamber. The timing, pressure, and duration of fuel injection is controlled by the electronic control module (ECM).

Electronic Control Module

The ECM is the computer that controls a Caterpillar engine. It includes the personality module (PM) which contains the software to control the ECM, and the engine governor which determines when, at what pressure, and how much fuel to deliver to the cylinders, based on actual and desired conditions at any given time. The timing, duration and pressure control of fuel is controlled by varying the signals to the injectors and the injection actuation pressure control valve.

Caterpillar industrial electronic engines include many standard features designed to improve performance, operating efficiency and emissions. The ECM constantly monitors engine speed and delivers only the amount of fuel needed to maintain the engine speed the user demands. Fuel is consumed more efficiently and the weight-to-horsepower ratio is improved.

Electronic fuel injection timing replaces all mechanical timing advance units, requires no timing feedback, and provides the flexibility to tailor the timing control to a specific injector family. It also improves cold starting by up to 20°F lower without assistance (ether controls are built into the ECM if an ether system is specified) from auxilliary starting devices.

Fuel temperature power compensation is provided to assure rated power and performance as fuel temperature changes. Sensors monitor the fuel and the ECM controls adjust power output to meet demand.

The ECM controls the air/fuel ratio using inlet manifold pressure and engine speed to maximize engine response while achieving the desired smoke emissions levels. This replaces the mechanical air/fuel ratio control and optimizes injector fuel delivery.

The highly efficient electronically controlled fuel delivery system provides for a lower weight-to-horsepower ratio (as compared to mechanically controlled engines) and allows for torque shaping. The ECM measures the actual engine speed, calculates the maximum fuel position, determines the required fuel position, and then selects the lowest value between the maximum fuel position and required fuel position. The fuel delivery rate is then increased, decreased or limited, as needed. The operator can also program the power trim (within limits) to guarantee exact engine power output.

Coolant/Oil Temperature Sensors

Coolant and oil temperature sensors are provided to improve cold start and warm-up operation. The sensors relay information to the ECM to optimize engine startability during cold mode cranking. It is used to lower the temperature at which ether aids, block heaters, or low viscosity lubricants are needed, providing quicker cold starts and reducing battery deep cycling.

As previously noted, the ECM provides electronic engine speed governing. The engine speed controls injector fuel delivery, and the injection duration is calculated to optimize engine response. The ECM receives input from the operator lever movement throttle position sensor to calculate and control engine speed. This eliminates mechanical throttle linkage and governor linkage adjustments. Also, the operator can easily determine and set the exact "power take-off" or "ramp-up" speed for a particular application.

Engine Monitoring System

The ECM continuously monitors engine, auxiliary, speed status and diagnostics. The ECM transmits this information through a data link to an optional engine monitoring system (EMS). The EMS provides engine and auxiliary analog and digital information for the operator. The following information can be displayed on the EMS:

- Engine speed
- Percent engine load

- Fuel rate/pressure
- Engine boost
- Battery voltage
- Engine coolant temperature
- Intake manifold temperature
- Fuel temperature
- Engine oil pressure
- Engine running hours

Warning Lamps

Red operating zones with associated alarms are set for engine oil pressure, coolant temperature, battery voltage and fuel pressure. In addition, warning lamps are provided for the following items:

- Coolant temperature
- Intake manifold temperature
- fuel temperature
- battery voltage
- accessory temperature
- engine oil pressure
- fuel pressure
- coolant level
- engine derate
- accessory pressure

Engine History Monitoring

The system also provides information management. The ECM provides engine history monitoring and calculates service intervals based on the application. The ECM records, stores and calculates information which can be retrieved using a service tool. The system records information before, during and after faults, so the operator can troubleshoot failures and diagnose problems. Information recorded and calculated for each application throughout engine life include the following:

- Instantaneous Information
  - Engine RPM
  - Percent Load
  - Fuel Rate
  - Temperatures
  - Pressures
  - Battery Voltage

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- Current Job
    - Hours
    - Fuel Used
    - Idle Time
    - Idle Fuel Used
    - Average Load Factor
- Lifetime Totals
    - Engine Hours
    - Total Fuel Used
    - Total Idle Fuel Used
    - Total Idle Time
    - Average Load Factor
- Histograms
    - Percent Load
    - Engine Speeds

Modern automotive engine electronic sensing and computer controls were developed over the past 25 years to significantly reduce emissions from the largest contributors to air pollution in California--mobile sources. They have done the job by optimizing engine operation, greatly improving efficiency and reducing fuel consumption to generate less pollutants. Also, they have improved destruction efficiencies of the remaining pollutants, primarily nitrogen oxides, carbon monoxide and hydrocarbons, through exhaust gas sensing and computer-controlled catalytic destruction processes.

As regulation and control of the major sources of air pollutant emissions--namely mobile sources and large stationary sources--have been implemented and proven beneficial, focus has increasingly shifted to smaller stationary sources. This is the reason for recent, more stringent regulation of stationary reciprocating engines, and subsequent industry response to reduce emissions with the assistance of technology developed within the automotive industry. Electronic sensing and computer controls have been successful in significantly reducing mobile source reciprocating engine emissions and are expected to be increasingly applied to controlling stationary reciprocating engine emissions for the same reason.

400 REGULATIONS

401 FEDERAL REGULATIONS

USEPA

The Federal Clean Air Act requires the U.S. Environmental Protection Agency (EPA) to establish new source performance standards (NSPS) for categories of sources which significantly contribute to air pollution. The NSPS apply both to new sources and to modifications to existing stationary sources of air pollution. The Clean Air Act directly prohibits operation of sources in violation of the NSPS. There is currently no NSPS specifically for stationary reciprocating engines, but engines are regulated by federal visible emission requirements and local regulations.

401.1 FEDERAL CLEAN AIR ACT

The Federal Clean Air Act Amendments were last developed in 1990. The main parts of the amendments include:

Title 1 - Nonattainment Areas
Mandates for the EPA to make regulations to bring nonattainment areas into attainment for CO, O_3, and particulate matter pollution.

Title 2 - Mobile Sources
Requirements for the EPA to issue regulations to reduce emissions from motor vehicles and automotive fuels.

Title 3 - Air Toxics
Requirements for EPA to issue standards to regulate 189 hazardous air pollutants.

Title 4 - Acid Rain
Mandates for EPA to issue new acid rain regulations, studies for NOx emissions, clean coal, and industrial SO_2 emissions.

Title 5 - Permits
Requirements for EPA to issue new rules for Permit approvals and source exemptions.

Titles 6+7 - Stratospheric Ozone and Global Climate Change
Requirements for EPA to create new regulations and perform studies.

Title 8 - Miscellaneous
Provisions for electric cars, regulations for outer continental shelf operations and visibility studies.

Title 9 - Research
Studies addressing air pollution health effects, clean fuels, ecosystems and other items.

401.2 NSPS

EPA has the authority to delegate enforcement authority. EPA has delegated primary authority to several local districts in California and to the State in those districts not seeking delegation. Therefore, the districts can enforce the EPA's regulations.

Code of Federal Regulations (CFR) Title 40 Part 60

Federal air pollution regulations for stationary sources are located in the New Source Performance Standards in the Code of Federal Regulations, Title 40 Part 60 (40 CFR 60). The NSPS contain subparts ranging from A to VVV that give standards for a multitude of different processes. There are no Federal regulations for stationary reciprocation internal combustion engines in the NSPS, but other Federal regulations, such as visible emissions and acid rain, can apply to them.

401.3 ACID RAIN PROVISIONS

Generally, any unit (fossil fueled combustion device) that commenced operation prior to November 15, 1990 is not affected by the acid rain rules. Any combustion device that commenced operation after this date and sells electricity may be an affected unit. Units that produce less than 25 MW of electricity for sale may be eligible to apply for an exemption from some of the acid rain rule requirements.

An affected unit must comply with acid rain regulations, including holding allowances sufficient to cover its annual SO_2 emissions, obtaining an acid rain Permit (which is part of the unit's general Permit), having a Designated Representative (DR), and installing and operating systems that continuously monitor emissions of SO_2, NOx and other related pollutants.

400 REGULATIONS

The only way an affected unit may avoid the full requirements of the acid rain program is by qualifying for an "exemption." Even if a unit is awarded an exemption, it is subject to certain minimum requirements. Exemptions and applicability determinations are made by the U.S. EPA Acid Rain Division in Washington, D.C. For more detailed information on the regulations, please refer to 40 CFR 72-78, or call the Acid Rain Hotline at (202) 233-9620.

40 CFR 72-78

Parts 72, 73, 74, 75, 76, 77, and 78 in the Code of Federal Regulations Title 40 deal with acid rain. Part 72 is the Permits Regulation, Part 73 is the Sulfur Dioxide Allowance System, Part 74 is Sulfur Dioxide Opt-Ins, Part 75 is the continuous emission monitoring and reporting requirements for affected units, and Part 76 is the Acid Rain Nitrogen Oxides Emission Reduction Program (This is only for coal fired devices).

Part 72 Permits Regulation
Subpart A-Acid Rain Program General Provisions - Sections 72.1 to 72.13

72.6 - Applicability (fossil fueled devices that must conform to regulation)
(a)1 and 2 - All fossil fuel fired devices listed in Table 1, 2 or 3 of 73.10.
(a)3, i and ii - All other fossil fuel fired devices except those that are new or did not have a capacity over 25 MW (megawatts) of electric power on 11/15/90 but did after 11/15/90.
(a)3, iii - Simple cycle gas turbines built as of 11/15/90, that had auxiliary firing added on after 11/15/90.
(a)3, iv - Previously exempt cogeneration facilities that sold during any three year period since 11/15/90 more than 1/3 of its potential electrical output capacity and more than 219,000 MW-hrs.
(a)3, v and vi - Fossil fuel fired devices that failed to meet the definition of a "qualifying facility" or an "independent qualifying facility" by 11/15/90.
(a)3, vii - A fossil fuel fired device that qualifies as a solid waste incinerator, but during any three years after 11/15/90 consumed 20% or more fossil fuel on a Btu basis.

Exemptions
(b)1 - Simple Cycle gas turbines that commenced operation before 11/15/90 are exempt.
(b)2 - Fossil fuel fired devices that commenced operation before 11/15/90 and do not generate more than 25 MW of electricity.
(b)3 - Fossil fuel fired devices that did not generate electricity for sale during 1985, as of 11/15/90, or currently.

(b)4, i - Cogeneration facilities that commenced construction on or before 11/15/90 to supply equal to or less than 1/3 of their potential electrical output capacity, or equal to or less than 219,000 MW-hrs. on an annual basis.
(b)4, ii - Cogeneration facilities that commenced construction after 11/15/90 and supply equal to or less than 1/3 of their potential electrical output capacity or equal to or less than 219,000 MW-hrs. on an annual basis.
(b)5, i - "Qualifying facilities" (see Section 72.2) that have one or more power purchasing commitments to sell at least 15% of their total net output capacity as of 11/15/90.
(b)5, ii - "Qualifying facilities" (see Section 72.2) that consist of one or more fossil fuel fired devices with a total net output capacity not exceeding 130% of the total planned net output capacity. If emission rates of the units are not the same the Administrator may exercise discretion in determining exempt units.
(b)6, i - "independent power production facilities" (see Section 72.2) that had one or more power purchasing commitments to sell at least 15% of their total net output capacity as of 11/15/90.
(b)6,ii - "independent power production facilities" (see Section 72.2) that consist of one or more fossil fuel fired devices with a total net output capacity not exceeding 130% of the total planned net output capacity. If emission rates of the units are not the same, the Administrator may exercise discretion in determining exempt units.
(b)7 - Solid waste incinerator exemptions.
(b)8 - "Non-utility units" (see Section 72.2) are exempt.
(c) Petitioning EPA Administrator for applicability.

72.7 New Units Exemption (those with a capacity less than 25 MW and burn fuel with less than 0.05% sulfur.)

72.8 Retired Units Exemption

72.9 Standard Requirements
(a)1, i - The designated representative of each source must submit a complete acid rain permit application.
(b) Monitoring requirements
(c) Sulfur dioxide requirements
(d) NOx requirements
(e) Excess emission requirements
(f) Recordkeeping and reporting requirements
(g) Liability

(h) Effect on other authorities
Subpart B - Designated Representative - Sections 72.20 to 72.25
Subpart C - Acid Rain Permit Applications - Sections 72.30 to 72.33
Subpart D - Acid Rain Compliance Plan and Compliance Options - Sections 72.40 to 72.44
Subpart E - Acid Rain Permit Contents - Sections 72.50 and 72.51
Subpart F - Federal Acid Rain Permit Issuance Procedures - Sections 72.60 to 72.69
Subpart G - Acid Rain Phase II Implementation - Sections 72.70 to 72.74
Subpart H - Permit Revisions - Sections 72.80 to 72.85
Subpart I - Compliance Certification - Sections 72.90 to 72.96

<u>Part 73 Sulfur Dioxide Allowance System</u>
Subpart A - Background and Summary - Sections 73.1 to 73.3
73.2 Applicability
(a) Owners, operators, and designated representatives of regulated sources under Section 72.6 (previous applicability section discussed for part 72)
(b) New "independent power producers" (see Part 72 definitions)
(c) Any owner of a regulated unit that may apply to receive allowances under the Energy Conservation and Renewable Energy Reserve Program
(d) Any small diesel refinery as defined in 72.2 (definitions)
(e) Any other person (defined in 72.2 definitions) who purchases, holds, or transfers allowances.

Standard requirements - The standard requirements of the previously mentioned Subpart 72 apply to Subpart 73 (Section 73.3 General). The requirements state that a permit application must be submitted.

Subpart B - Allowance Allocations - Sections 73.10 to 73.27
Subpart C - Allowance Tracking System - Sections 73.30 to 73.38
Subpart D - Allowance Transfers - Sections 73.50 to 73.53
Subpart E - Auctions, Direct Sales, and Independent Power Producers Written Guarantee - Sections 73.70 to 73.77
Subpart F - Energy Conservation and Renewable Energy Reserve - Sections 73.80 to 73.86
Subpart G - Small Refineries - Section 73.90

<u>Part 74-Sulfur Dioxide Opt-Ins</u>
Subpart A - Background and Summary - Section 74.1 to 74.4

74.2 Applicability
Combustion or process sources that are not regulated under Section 72.6 (applicability) that are operating and located in the lower 48 States or the District of Columbia may submit an Opt-In permit. Units under 72.7 or 72.8 under written exemption and combustion or process sources are not eligible.

Subpart B - Permitting Procedures - Sections 74.10 to 74.19
Subpart C - Allowance Calculation for Combustion Sources - Sections 74.20 to 74.28
Subpart D - Allowance Calculation for Process Sources (Reserved)
Subpart E - Allowance Tracking and Transfer and End of Year Compliance - Sections 74.40 to 74.50
Subpart F - Monitoring Emissions: Combustion Sources - Sections 74.60 and 74.61
Subpart G - Monitoring Emissions: Process Sources (Reserved)

<u>Part 75 - Continuous Emission Monitoring</u> (40 CFR 75)
Subpart A - General - Sections 75.1 to 75.8
75.2 Applicability
(a) All units that are subject to acid rain emissions limitations or reduction requirements for sulfur dioxide or NOx.
exemptions:
(b) New units that have a nameplate capacity of 25 MW or less and burn fuel with a sulfur content of 0.05% by weight or less.
(b)2 - Units not subject to the requirements of the acid rain program (see 72.6).
(b)3 - A unit subject to the regulation that has been issued a written exemption under 72.8 and granted an exception granted under 75.67.

Subpart B - Monitoring Provisions - Sections 75.10 to 75.18
75.10 General
(a) The owner or operator shall measure opacity, SO_2, NOx, and CO_2 for all units subject to the regulation.
75.11 Monitoring SO_2
75.12 Monitoring NOx
75.13 Monitoring CO_2
75.14 Monitoring opacity
75.16,17,18 Monitoring for bypass stacks, multiple stacks and other provisions.
Subpart C - Operation and Maintenance Requirements - Sections 75.20 to 75.24
Subpart D - Missing Data Substitution Procedures - Sections 75.30 to 75.36

Subpart E - Alternative Monitoring Systems - Sections 75.40 to 75.48
Subpart F - Recordkeeping Requirements - Sections 75.50 to 75.56
Subpart G - Reporting Requirements - Sections 75.60 to 75.67

Part 77-Excess Emissions
77.1 Purpose and Scope
Excess emission offset planning and offset planning requirements. Applies to owners, operators and designated representatives subject to the Acid Rain Program.
77.2 General
77.3 Offset Plans for Excess Emissions of Sulfur Dioxide
(a) Applicability - Any owner or operator subject to the regulation that has emissions of sulfur dioxide in any calendar year shall be liable to offset the amount of such excess emissions by an equal amount of allowances from the "Allowance Tracking System" (see part 72.2, Definitions) account.
(b) Deadline - No more than 60 days after the end of any calendar year in which a unit had excess sulfur dioxide emissions.
(c) Number of Plans
(d) Contents of Plan

77.4 Administrator's Action on Proposed Offset Plans
77.5 Deduction of Allowances to Offset Excess Emissions of Sulfur Dioxide
77.6 Penalties for Excess Emissions of Sulfur Dioxide and Nitrogen Oxides

Part 78 - Appeal Procedures for Acid Rain Program - Sections 78.1 to 78.20

401.4 TITLE V OPERATING PERMIT PROGRAM

Title V is a Federal EPA operating permit program to track emissions from large sources (Title 40 CFR Part 70). Sources with over 100 tons/year of emissions, over 10 tons/year of hazardous pollutants, or sources subject to nonattainment provisions are subject to Title V. **40 CFR 70**

401.5 PREVENTION OF SIGNIFICANT DETERIORATION (PSD)

Prevention of Significant Deterioration is a program designed to prevent the deterioration of air quality, especially in areas that are in attainment or are relatively free of air pollution. The regulation for prevention of significant deterioration of air quality is located in 40 CFR 52.21. Facilities may be required to meet the limits of this regulation depending on the amount of emissions released from it. The regulation limits emissions from facilities under the regulation by the federal class designation of the land where the facility is located (i.e. national recreation area, national monument, national wild and scenic river etc.).

401.6 NONROAD DIESEL EMISSIONS

On September 24, 1997, the Federal Register reported that the USEPA had proposed a new rule for the, "Control of Emissions of Air Pollution from Nonroad Diesel Engines." The affected engines are used in most land-based nonroad equipment and some marine applications. If these standards are implemented as proposed, the new federal standards for nitrogen oxides and particulate matter emissions would be reduced by up to two-thirds from current standards for engines in this large category of pollution sources. The proposed program would provide much-needed assistance to states facing ozone and particulate air quality problems.

A first set of federal emission standards, called "Tier 1" standards, was issued for land-based nonroad diesel engines rated at or above 37 kW (50 hp) on June 17, 1994. As a result, manufacturers of these engines are beginning to address the emissions of their products. For nonroad diesel engines rated below 37 kW, no federal emission standards currently exist.

402 STATE REGULATIONS

State laws and statutes applicable to air pollution are in the California Health and Safety Code. Applicable Health and Safety Code requirements are in Appendix B.

California Health & Safety Code (CCR)

CCR Titles 17, 26

Specific State regulations regarding air pollution are developed by the California Air Resources Board and are included in the California Code of Regulations (CCR). Title 13 contains regulations for mobile sources (cars, trucks etc.), Title 17 contains stationary source regulations, and Title 26 contains toxics regulations. The Air Resources Board of the State of California primarily performs regulation and enforcement for mobile sources, consumer products, fuels, and abrasive blasting.

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402.1 CALIFORNIA CLEAN AIR ACT

There is also a California Clean Air Act which went into effect in 1988. It basically requires the following:

1. The attainment of the State ambient air quality standards by the earliest practicable date.

2. All districts in violation of the State ozone, carbon monoxide, sulfur dioxide, or nitrogen dioxide standards must submit attainment plans every three years.

3. The California Air Resources Board must adopt the most effective emission controls possible for motor vehicles, fuels, consumer products, and mobile sources.

4. Districts subject to planning requirements must reduce emissions 5% a year until the relevant standard is achieved.

5. Rules and regulations within air basins must be uniform to the extent practicable, and the districts must coordinate individual planning efforts so that regional air quality issues are adequately addressed.

402.2 STATE IMPLEMENTATION PLAN (SIP)

The State Implementation Plan (SIP) is a plan that must be delivered to the federal EPA describing how the state will run its air quality control programs in order to attain the National Ambient Air Quality Standards.

402.3 UTILITY AND LAWN AND GARDEN ENGINES

State regulations for utility and lawn and garden engines are located the California Code of Regulations, Title 13, Chapter 9, Article 1, Section 2400. The regulation applies to engines built after 1/1/95. These engines are under 25 horsepower and are typically used for lawn mowers, chain saws, edge trimmers, etc. Some of the main requirements in the rule include an executive order issued for the engine, labeling requirements, and emission standards (Table 402.1).

Table 402.1 Utility and Lawn and Garden Engine Emission Limits (g/Bhp-hr)						
Year	Type & Size	HC + NOx	HC	CO	NOx	PM
'95-'98	< 25 cc; Non hand held	12	--	300	--	0.9
	> or = to 25 cc; Non hand held	10	--	300	--	0.9
	< 20 cc; hand held	--	220	600	4	--
	20 to 50 cc; hand held	--	180	600	4	--
	over 50 cc; hand held	--	120	300	4	--
'99 and later	all	3.2	--	100	--	0.25
		--	50	130	4	0.25

402.4 PORTABLE ENGINES

The Statewide Portable Equipment Registration Program (Program) was adopted on March 27, 1997 by the ARB. On September 17, 1997, it became law. The Program regulates portable engines and portable engine-driven equipment units. Once registered in the Program, engines and equipment units can be operated throughout the state of California without the need to get individual permits from local air districts. Districts are preempted from permitting, registering, or regulating units registered with the ARB; however, local air districts are responsible for enforcing the Program.

A portable engine is an internal combustion engine which can be moved from one location to another and does not remain at a single location for more than twelve consecutive months. A portable equipment unit is a portable piece of engine-driven equipment which is associated with, and driven solely by, a portable engine and emits pollutants over and above the emissions of the portable engine.

Portable engines include, but are not limited to, internal combustion engines used in the following:

- cranes
- pumps
- welding
- well drilling
- woodchippers
- power generation
- diesel pile-driving hammers
- service or work-over rigs
- dredges on boats or barges
- compressors

Portable equipment units include, but are not limited to, the following portable engine-associated units:

- abrasive blasting operations
- concrete batch plants
- sand and gravel screening and rock crushing
- pavement crushing and recycling operations

Portable engines and portable equipment units that meet the definitions of the Program are eligible for registration. Registered engines must comply with technological requirements which may include 4-degree injection timing retard, turbochargers, aftercoolers, or catalysts. In addition, some portable engines may be required to meet established emission limitations, fuel specific requirements, and recordkeeping and reporting requirements.

Portable equipment units registered in the Program must comply with established Best Available Control Technology requirements. Additional registration requirements include a daily emission limit of 82 pounds per day of particulate matter smaller than 10 microns in diameter (PM-10), an annual limit of 10 tons per year for any criteria pollutant, and recordkeeping and reporting requirements.

The local air districts have primary enforcement responsibility. The ARB or the districts may conduct inspections at any time to verify and ensure compliance with the Program requirements. A district may charge $75 to inspect a portable engine or equipment unit. The ARB will collect fees for registration, renewal, and associated administrative tasks. The cost to register under the Program is $90 per portable engine or portable equipment unit.

Table 403.1 Bay Area AQMD - Main Standards for Stationary Reciprocating ICEs				
Regulation	Fuel Type	Engine Type	Emission Limits (ppmv at 15% O2 on a dry basis) effective 1/1/97	
			NOx	CO
9-8-301.1	Fuel gas	Rich burn	56	2000
9-8-301.2	Fuel gas	Lean burn	140	
9-8-301.3	Fuel gas	All	——	
9-8-302.1	Liquid, gas, waste gas	Lean burn	140	2000
9-8-302.2	Liquid, gas, waste gas	Rich burn	210	
9-8-302.3	Liquid, gas, waste gas	All	——	

Table 403.2 Kern Desert Zone - Main Standards for Stationary Reciprocating ICEs				
Regulation	Engine Type	Emissions Limit (ppmv) averaged over 15 min. at 15% O2, on a dry basis		NOx Control Device Efficiency
		NOx	CO	
427 VI, A	Rich burn	50	2000	90%
427 VI, B	Lean burn	125	2000	80%
		Engines controlled exclusively by combustion modifications: NOx = 2 g/Bhp-hr maximum		
427 VI, C	Diesel	600	2000	30%
427 VI, D	For Engines with a demonstrated thermal efficiency over 30%, emissions may be determined by multiplying the emission limit above by the engine thermal efficiency and dividing by 30%. Engine efficiency is the higher of the following two equations: E = [(3413 Btu/Bhp-hr)100]/Actual heat rate at HHV (Btu/Bhp-hr) or E = (Mftrs rate efficiency [continuous] at LHV)LHV/HHV E cannot be less than 30%			

Table 403.3 Sacramento AQMD Main Standards for Stationary Reciprocating ICEs				
Regulation	Engine Type	Emission Limits (ppmv at 15% O2)		
		NOx	CO	NMHC
301 (RACT)	Rich burn	50	4000	250
	Lean burn	125	4000	750
	Diesel	700	4000	750
302.1	Rich burn	25	4000	250
302.2	Lean burn	65	4000	750
302.3	Diesel	80	4000	750
303	As an alternative, NOx control device efficiency must be 90% or greater.			

Table 403.4 San Diego APCD - Main Standards for Stationary Reciprocating ICEs				
Regulation	Engine Type or Fuel Type	Emissions Limit (ppmv) at 15% O2, on a dry basis		NOx Control Device Efficiency *
		NOx	CO	
69.4, 1, i; 69.4, 1, ii and 69.4, 2	Rich burn	50	4500	90%
	Lean burn	125		80%
	Waste gas	125		80%
	Diesel or kerosene	700		25%
69.4, 1, ii	*An engine may meet the emission limit, OR have a control device with the complying efficiency.			
69.4, 3	The owner or operator of the engine must conduct annual maintenance as recommended by the manufacturer or stated by the APCO.			

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<table>
<tr><th colspan="5">Table 403.5 SJVUAPCD Main Standards for Stationary Reciprocating ICEs</th></tr>
<tr><td rowspan="2">Regulation</td><td rowspan="2">Engine Type</td><td colspan="2">NOx</td><td rowspan="2">CO (ppmv)</td></tr>
<tr><td>g/bhp-hr</td><td>ppmv</td></tr>
<tr><td rowspan="3">4701, 5.1</td><td>Rich burn</td><td>9.5</td><td>640</td><td>2000</td></tr>
<tr><td>Lean burn</td><td>10.1</td><td>740</td><td>2000</td></tr>
<tr><td>Diesel</td><td>9.6</td><td>700</td><td>2000</td></tr>
<tr><td colspan="5">Natural gas fired engines in central and western Kern fields, except cyclic loaded engines, and those that were not in compliance by 5/31/95.</td></tr>
<tr><td>Regulation</td><td>Engine type</td><td>NO (ppmv at 15% O2)</td><td>CO (ppmv at 15% O2)</td><td>Min. NOx control device efficiency *</td></tr>
<tr><td rowspan="3">4701, 5.2;
4701, 5.2.1;
4701, 5.2.2;
4701, 5.2.3</td><td>Rich burn</td><td>90</td><td>2000</td><td>90%</td></tr>
<tr><td>Lean burn</td><td>150</td><td>2000</td><td>70%</td></tr>
<tr><td>Diesel</td><td>600</td><td>2000</td><td>30%</td></tr>
<tr><td></td><td colspan="4">*Engine can meet emission limits, OR control device limits.</td></tr>
<tr><td>4701, 5.3</td><td colspan="4">Owner or operator may permanently remove engine or replace it with an electric motor. ATC must have been submitted by 5/1/97 and engine must be removed by 5/31/99.</td></tr>
</table>

Table 403.6 Santa Barbara APCD - Main Standards for Stationary Reciprocating ICEs

Regulation	% O2	Engine Type	Emission Limits (ppmv)			NOx control device efficiency
			NOx	ROC	CO	
333 D,1	15	Rich burn	50	250	4500	90%
	3		152	758	13653	
333 D,2	15	Lean burn	125	750	4500	80%
	3		380	2275	13653	
333 D,3	15	Cyclic	50	250	4500	
	3		152	758	13653	
333 D,4	15	Diesel	797	------	------	
	3		2400	------	------	

403 LOCAL (DISTRICT) REGULATIONS

Most of the regulation and enforcement is conducted by county air pollution control districts (APCDs) or multi-county air quality management districts (AQMDs). Districts regulate with their rules and by issuing Permits to Operate to companies owning or operating pollution generating equipment. Permits to Operate help simplify requirements in complex regulations for facility operators and owners, so they can usually comply with most requirements by following their Permit. When a facility does not comply with a Permit or rule it may be given a Notice of Violation (NOV) and fined. Districts can also enforce the EPA rules and many have directly adopted the NSPS and NESHAPS regulations. In some cases district regulations are more stringent than the EPA's. District regulations cannot be less stringent than the EPA's.

403.1 DISTRICT STATIONARY RECIPROCATING ENGINE REGULATIONS

Most of the heavily populated districts and districts with large industries have rules exclusively for stationary reciprocating engines. As of the time of the printing of this manual, the following districts had rules for reciprocating engines: Bay Area Air Quality Management District (BAAQMD), Sacramento Metropolitan Air Quality Management District (SMAQMD), San Diego Air Pollution Control District (SDAPCD),

Table 403.7 South Coast AQMD - Main Standards for Stationary Reciprocating ICEs				
Regulation	Engine Type	Emission Limits (ppmv averaged over 15 min. at 15% O2, on a dry basis)		NOx control device efficiency *
		NOx	CO	
1110.1 c,1,A	Rich burn	90	2000	90% initially, 80% thereafter
1110.1 c,2,A	Lean burn	150		80% initially, 70% thereafter
1110.1 c,2,B		2 g/Bhp-hr or 150 ppmv	Engines controlled by combustion modifications	
1110.1 c,1,A and c,2,A	*Engines must meet the emission concentrations above, OR be equipped with a complying control device.			
1110.1 c,3	Owners or operators must submit a control plan for the reduction of emissions to meet the limits above. The plan must include: a list of all the engines, the permit or I.D. numbers and the type of engine service; the manufacturer, model, rated Bhp, fuel, and ignition type; and the engines controlled, the type of emission controls and construction schedules (except on cyclic engines of 200 hp or less).			
1110.2 c,1 and c,2	The owner or operator of any engine must replace it with an electric motor or reduce CO to 2000 ppmv, NOx to 36 ppmv, ROC to 250 ppmv at 15% O2 on a dry basis averaged over 15 min.			

Table 403.8 South Coast AQMD - Main Standards for Stationary Reciprocating ICEs (continued)			
Regulation	Emission Limits (ppmv averaged over 15 min. at 15% O2, on a dry basis)		
	NOx	ROG	CO
1110.2 c,2,A	36	250	2000
1110.2 c,1 and c,2	The owner or operator of any I.C. engine must replace it with an electric motor or reduce emissions to the compliance limits above.		
1110.2 c,2,B	Owners or operators of any electrical power generation, portable, landfill gas, digester gas, water pump (except aeration facilities), oil field, compressor application engine (operating less than 4000 hours per year), or LPG fired engine may reduce emissions of NOx and ROG by the following compliance limit (the CO limit is 2000 ppmv): Compliance Limit = [Reference Limit](EFF/25%) Compliance Limit = Allowable NOx or ROG emissions (ppm by volume) Reference Limit = The NOx or ROG emission limit (ppmv) corrected to 15% O2, dry, averaged over 15 min.		
	Reference Limits (ppm)		
	Bhp rating (hp)	NOx	ROG
	500 and greater	36	250
	50 to 500	45	250
	Eff = [3413(100%)]/Actual heat rate at HHV of fuel (Btu/kW-hr) = % efficiency at full load averaged over 15 min., within 30 days of the 1st source test, without consideration of downstream energy recovery equipment, corrected to the HHV of the fuel as measured at peak load. -Or- Eff = (Manuf. Rated Efficiency at LHV)(LHV/HHV) = Manufacturer's continuous rated % efficiency of engine after correction from LHV to HHV of fuel (whichever efficiency is higher). Eff can't be less than 25%. If the efficiency is below 25% it is assigned a value of 25%.		

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Table 403.9 Ventura County APCD - Main Standards for Stationary Reciprocating ICEs

Regulation	Engine Type	Fuel Type	Emissions Limits (ppmv) as of 1/1/97 *			NOx Limit with Control Device (% Reduction) as of 1/1/97 *
			NOx	ROC	CO	
74.9, B,1 and 74.9, B,2	Rich burn	General	25	250	4500	96
	Lean burn		45	750	4500	94
	Diesel	——	80	750	4500	90
	Rich burn	Waste gas	50	250	4500	——
	Lean burn	Waste gas	125	750	4500	——
74.9, J,2	*Complying engines installed after 9/5/89 must meet these limits by1/1/02					
			Emissions before 1/1/97 or 1/1/02 (gm/Bhp-hr)/ppm			NOx (% Reduction before 1/1/97 or 1/1/02)
74.9, B,3	Rich burn	——	0.805/50	–/250	–/4500	90
	Lean burn	——	2.42/125	–/750	–/4500	80
74.9, B,4	Emission limits may be multiplied by X where X = E/0.3 and E = engine efficiency. Engine efficiency is the higher of the two equations: E = [(Engine output)100]/Energy input or E = (Mftrs rate efficiency [continuous] at LHV)LHV/HHV E cannot be less than 30%					
74.9, B,5	No emissions of ammon ia from any emission control device over 20 ppmv					

San Joaquin Valley Unified Air Pollution Control District (SJVUAPCD),
San Luis Obispo County Air Pollution Control District (SLOCAPCD),
South Coast Air Quality Management District (SCAQMD),
Santa Barbara County Air Pollution Control District (SBAPCD),
Ventura County Air Pollution Control District (VCAPCD), and the
Yolo-Solano Air Quality Management District (YSAQMD).

Districts that don't have a rule for reciprocating engines use their fuel burning equipment rule or control of NOx rule and their sulfur content of fuels rule to regulate sources that are not exempt from permitting.

Table 403.10 Yolo-Solano AQMD Main Standards for Stationary Reciprocating ICEs				
Regulation	Engine Type	NOx		CO (ppmv)
		g/hp-hr	ppmv	
301.1	Rich burn	9.5	640	2000
	Lean burn	10.1	740	2000
	Diesel	9.6	700	2000
401.2	Emission limits as of 5/31/97			
		NO (ppmv)	CO (ppmv)	
301.2	Rich burn	90	2000	----
	Lean burn	150	2000	----
	Diesel	600	2000	----
301.3	Owner or operator may permanently remove engine or replace it with an electric motor. ATC must have been submitted by 1/1/97 and compliance must be demonstrated by 5/15/99.			

Most of the rules in the different districts are set up in a similar fashion. In general, they usually begin with general information about the regulation, definitions or with an applications section. The definitions section describes the meanings of important words as they pertain toward the rule. The applications section describes what kind of equipment applies to the rule. In stationary internal combustion engine regulations, districts may have a statement limiting regulation of engines to those above 50 hp.

The standards section describes the emission limitations. Note that the standards for the concentration (volume basis or ppmv) of NOx emissions in district regulations are at 15% O_2 on a dry basis. This prevents a facility from complying with emission concentrations in the exhaust by diluting it with air. "On a dry basis" also means that water in the exhaust will not be counted when emission concentrations are determined. Regulations may also limit pollutants on a mass basis i.e., g/bhp-hr. Tables 403.1 to 403.10 summarize the standards of the districts with regulations on stationary reciprocating engines. For specific requirements refer to your district rule.

Between different districts, the sections in a regulation that appear after the standards section can vary somewhat, but they generally have the same kind of information. Some regulations have an administrative requirements section. Other rules, such as the South Coast AQMD rule on stationary internal combustion engines, have a compliance schedule section and an emission control plan section. These parts of the rules often have information on different requirements of the rule that must be complied with over time. Items in these parts of the rule may also require owners or operators of the equipment to submit plans by specific dates to illustrate how they will comply with the rule. Many district rules often describe equipment monitoring requirements and recordkeeping requirements in the monitoring and recordkeeping section.

Besides a district's reciprocating engine or internal combustion engine rule, other rules such as those that regulate carbon monoxide, particulate and sulfur dioxide emissions can apply to reciprocating engines.

403.1.1 Exemptions

District rules often have an exemption section where equipment that does not have to comply with the rule is described. This section may occur at the end of the regulation, but some district rules have it at the beginning. Some typical situations where reciprocating engines are exempt and do not have to comply with regulations are when they are for emergencies and operate less than a specific amount of time per year (such as 200 hours). Engines used for laboratory research, firefighting, agriculture, or flood control are often exempt from regulations.

When stationary engines (especially diesel engines) are started, emissions can be high, and it takes time for catalysts to warm up and become effective. Usually these high smoke emission do not last long enough to create a visible emissions violation.

403.2 VISIBLE EMISSIONS

All of the local air pollution control districts in California have a visible emissions prohibitory rule. These rules vary in wording, but in almost all cases they express the following:

"... no person shall discharge into the atmosphere from any source whatsoever any contaminant, other than uncombined water vapor, for a period or periods aggregating more than three minutes in any one hour which is:

(a) As dark or darker in shade as that designated as No. 1 (or 20% opacity, see Table 403.11) on the Ringelmann Chart, as published by the United States Bureau of Mines,

(b) Or of such opacity as to obscure an observer's view to a degree equal to or greater than does smoke described in subdivision (a)."

The State standard for visible emissions (Section 41701, California Health and Safety Code) is No. 2 on the Ringelmann Chart, or 40% opacity.

Opacity, Ringelmann

The Ringelmann Chart is a device used for determining whether emissions of smoke are within established limits or standards of permissibility (statutes and ordinances) with reference to the Ringelmann Chart. Smoke density in a plume is compared with a series of graduated shades of gray to black on the Ringelmann Chart, and the smoke density is thus judged by the viewer. EPA Reference Method 9 describes in detail how such visible emissions evaluations should be properly performed, and how to be certified to perform them.

The Compliance Division of the California Air Resources Board trains and certifies government and industry personnel in visible emissions evaluations at its popular "Fundamentals of Enforcement" class which is offered four times a year. Certified personnel are required to recertify every six months in order to demonstrate ongoing evaluation skill.

When reducing the data, the inspector should aggregate the readings taken at 15-second time intervals where the opacity was observed to exceed the Ringelmann limit. Every aggregate of over three minutes of such readings, made in a one hour period, constitutes a violation. This data reduction method reflects the visible emissions limitation in California Healthy and Safety Code (H&SC) Section 41701. Note that this procedure of data reduction results in more stringent emissions limitations than the Federal method as stated in Method 9. According to Method 9, opacity is determined as an average of 24 consecutive observations recorded at 15-second intervals (i.e., six consecutive minutes of readings, averaged).

403.3 SULFUR OXIDE EMISSIONS

District rules specifically for stationary internal combustion engines generally do not have limits for sulfur oxide emissions. The amount of sulfur for a combustion process is often limited by the percent-by-weight of sulfur in the fuel. The percent-by-weight of sulfur in a fuel may be limited in a fuel burning rule or a fuel burning equipment rule.

Some district sulfur emissions rules limit the stack discharge concentration to a specified ppm from any combustion operation. Other rules require that a process not emit enough sulfur compounds to exceed the State or federal standards at the ground level (0.05 ppm, by volume, for 24 hours average, or 0.25 ppm, by volume, for 1 hour average).

403.4 DISTRICT PERMITS TO OPERATE

Under the authority of the California Health and Safety Code, and in order to comply with the California State Implementation Plan and New Source Performance Standards where applicable, the districts issue Permits to Operate which contain conditions for the operation of industrial processes and emission control equipment. The Permit conditions in a Permit to Operate generally reflect the requirements of the rules that apply to a source.

Facilities must function within the parameters stated in the Permit to Operate issued by the district. Permits must be posted on the equipment, where applicable, and they must be current. If these conditions are not adhered to, it is a violation.

Permits have an equipment list, listing the equipment they cover. It is a violation to operate pollution generating or control equipment that is not permitted when regulations require a permit. It is also a violation to make modifications to permitted equipment without district approval. When new

Table 403.11 Relationship Between Light Transmission, Ringelmann and Opacity		
% Light Transmission	Ringelmann	Opacity
0	5	100
20	4	80
40	3	60
60	2	40
80	1	20
100	0	0

equipment or modifications are required, a district will issue an Authority to Construct to the owner or operator of the equipment.

Whenever a company must make a modification to its equipment or buy new equipment, it should notify its local district immediately. A district can usually accommodate a source even when modifications must be made in a short period of time.

An Authority to Construct will list the equipment to which it applies and it will list conditions similar to those on a Permit to Operate. After the new equipment is modified or constructed the district may conduct a source test and issue a Permit to Operate.

Some typical conditions stated on a Permit to Operate on an operation using a stationary reciprocating engine include:

1. Fuels that can be burned in the reciprocating engine.

2. The number of hours of operation allowed per year (especially for emergency engines).

3. Emission limits.

4. Required emission control equipment.

5. Recordkeeping requirements.

6. Requirements for continuous emission monitors.

403.5 EQUIPMENT BREAKDOWN PROVISIONS

Each district has an equipment breakdown (or excusable equipment malfunction) rule. The rule enables a source qualifying under stated conditions to avoid enforcement action otherwise precipitated by failure of that source to comply with air pollution regulations as a result of a malfunction of any air pollution control equipment or related operating equipment. Malfunctions of in-stack monitoring equipment are also addressed in the rule.

Sources should keep a copy of the breakdown rule on location. They should also be familiar with their responsibilities in the event of an equipment malfunction.

Breakdown Conditions

The conditions that a malfunction must meet in order to qualify for district breakdown provisions vary from district to district. Typically, the following are conditions for an acceptable breakdown:

1. The breakdown must result from a failure that was unforeseeable;
2. It must not be the result of neglect or disregard of any air pollution control law or rule or regulation;
3. It must not be intentional, or the result of negligence;
4. It must not be the result of improper maintenance;
5. It must not constitute a nuisance; and
6. It must not be an abnormally recurrent breakdown of the same equipment.

Breakdown Procedures

District rules also list a number of procedures which must be followed in reporting the breakdown in a timely manner to the district. If the breakdown is not reported to the district within the allowed time period, as stated in the rule, a separate violation occurs, for which enforcement action is appropriate.

When a breakdown is reported to the district it is recorded in the district's breakdown log. Sources must provide the district with the following information:

1. The source's name and location, and the source contact's name and telephone number;
2. The specific equipment affected by the breakdown;
3. The specific equipment that failed;
4. The date and time that the breakdown occurred;
5. The date and time that the breakdown is being reported to the district; and
6. The source's proposed action.

Breakdown Report

Upon receipt of a breakdown report, the district performs an investigation to determine whether the malfunction meets the prescribed breakdown conditions. This investigation includes an onsite inspection of the malfunctioning equipment. If the inspector does not find a breakdown condition at the source, he may take appropriate enforcement action including, but not limited to, seeking fines, an abatement order, or an injunction against further operation.

If a source files a breakdown report which falsely, or without probable cause, claims a malfunction to be a breakdown occurrence, this shall constitute a separate violation. The burden of proof shall be on the source to provide sufficient information that a breakdown did occur. If the source fails to do this, the district will undertake appropriate enforcement action.

A source with a breakdown must take immediate steps to correct the equipment malfunction as quickly as possible. If a source finds that a malfunction cannot be repaired within the district's allowable duration of a breakdown, the source may file for an emergency **variance** in order to avoid enforcement action.

Correction

District rules require sources to submit in writing the following details to the district air pollution control officer within a stated time period of the correction of the breakdown occurrence:

1. The duration of excessive emissions;
2. An estimate of the quantity of excess emissions;
3. A statement of the cause of the occurrence;
4. Corrective measures to be taken to prevent recurrences; and
5. Proof of the source's return to compliance, including the date and time that the breakdown was corrected.

Besides the information mentioned above, the district log will also include the following items, some of which will be filled in as the case continues:

1. A confirmation that the breakdown is allowable under district rules;
2. The name of the district investigator;
3. The initial inspection file number;
4. The compliance confirmation inspection file number;
5. The date that the breakdown correction report was filed by the source; and
6. An indication if a variance was requested.

403.6 VARIANCES

A source may petition for a variance if either of the following is true:

1. Pollution control equipment has broken down and meets the criteria for breakdown condition under district rules; however, the source operator finds that it will take longer to repair the breakdown than provided for under the district breakdown rule. In such a case, a source operator may wish to apply for an emergency variance.

2. A source finds itself to be out of compliance, is found to be out of compliance, or expects to soon be out of compliance, with any air pollution control district rule or regulation, or with Section 41701 of the California Health and Safety Code (H&SC).

If a source falls into either of the above categories at any time, it should consider applying for a variance. A source's purpose in applying for a variance is to attempt to shield itself from state and local enforcement action while it is out of compliance. Federal regulations do not have a variance provision and a variance cannot protect against federal enforcement actions. Sources should be advised that the initiative to file for a variance and to prove that they need a variance rests on them.

Interim Variance

A source can apply for a short variance (90 day maximum) or a regular variance (over 90 days and 1 year maximum unless a schedule of increments of progress is included). Interim variances are also available which gives the source protection from enforcement action until their original application for variance can be noticed and heard by the hearing board, or up to 90 days, whichever is shorter. Interim and emergency variance orders, if issued, are typically granted the same day they are requested. A written petition must be submitted before these (and all other) variances are granted.

It is the source's responsibility to estimate the amount of time it will need to be under variance, and to then apply for the appropriate type of variance.

A source should be aware that the decision on whether to grant any variance rests with the district variance hearing board and not with the air pollution control officer or that person's staff.

Rules for variance procedures vary from district to district. The district rules are based on H&SC statutes, however, in some districts the rules are stricter than H&SC requirements. Some of the applicable statutes are listed in Section 505 of this manual. District personnel as well as source operators should be familiar with these statutes and with the any local district variance rules.

H&SC Requirements

With regard to variances, State law (H&SC) requires that:

1. The district should not allow sources to operate in violation of district rules without a variance, even if the source is working towards finding a solution to the problem. Source operators should be aware that under H&SC Section 42400.2, if they continue to operate in violation of district rules, they are subject to a $25,000 per day fine and up to 12 months in county jail.

2. All variance hearings should be noticed properly in accordance with H&SC Sections 40823 through 40827. Section 40826 requires a 30-day notice period for hearings for variances over a 90-day duration.

3. No variance shall be granted unless the hearing board makes all of the findings listed in H&SC, Section 42352.

CARB Recommendations

The Air Resources Board recommends that the following procedures be observed in the various stages involved from the time a source petitions for a variance through the end of the variance period. Some of these recommendations may not be a part of all districts variance programs at this time; or, they may be written but not implemented procedures.

1. Parties petitioning for variances should be required to fill out a petition form in writing.

2. The district will require sources to provide excess emissions figures on the petitions they submit. This information will be evaluated by the district staff. The emission figures are presented to the hearing board, so that the

board formally recognizes, and the public may be aware of, the emissions impact of the variance. If the variance is granted, these limits must be included in the final variance order.

3. An interim variance can be granted to cover the time period from filing the petition for a regular or short variance until a decision is rendered on whether the variance is granted. This interim variance can subject the source to operating conditions during that interim period.

4. Variances should not be granted retroactively. The date that variance coverage begins cannot predate the date on which the petition was filed.

5. Each variance order will specify the equipment under variance and the district rule or regulation violated.

6. The district should schedule increments of progress for sources under variance. Increments of progress are required for variances over one year. District staff should verify that the source is meeting these increments of progress.

7. The district should require the source to quantify excess emissions that will occur during the period of variance.

8. At the end of the variance period, the district shall inspect the source to ensure that it is in compliance with all district air pollution regulations.

403.7 NEW SOURCE REVIEW RULES

Every district has a new source review rule which is intended to prevent the deterioration of air quality from new or modified sources with the least negative impact on economic growth. New source review rules are required as part of California's State Implementation Plan (SIP).

When a new source is constructed an Authority to Construct is required. This allows the district to calculate the emissions and make sure the source will comply with the new source review rule. The district will have a threshold of emissions that will require the source to use Reasonably Available Control Technology (RACT), Best Available Retrofit Technology (BARCT), Best Available Control Technology (BACT). The nonattainment designation of an area determines which control must be used. These designations include moderate, serious, severe and extreme. The level of ozone and carbon monoxide determines the area's designation (Health & Safety Code Section 40921).

403.7.1 RACT, BARCT, BACT

Reasonably available control technology (RACT) is a level of emission control technology that is currently achieved and demonstrated. RACT is required for moderate nonattainment areas (Health and Safety Code Section 40918).
Best available retrofit control technology (BARCT) is a level of emission control technology that is currently achieved, but not necessarily demonstrated. BARCT takes into account environmental, energy and economic impacts of using a given emission control system. RACT will never be stricter than BARCT, but the two may require controls that are equivalent. New or modified permitted sources in moderate nonattainment areas with emissions over 250 tons per year require BARCT, and all permitted sources in serious nonattainment areas require BARCT (Health & Safety Code Sections 40918 and 40919).

BACT is the best emission control technology available that has been achieved in practice or demonstrated. It does not take into account economic considerations, therefore it is an emission control that is as strict or stricter than RACT or BARCT. Each district has listings illustrating the BACT for every type of source, including everything from reciprocating engines to automotive refinishing. California air districts generally base their BACT on the South Coast AQMD BACT. On the other hand, the emissions trigger level of different districts will vary widely because of their nonattainment designation. In the South Coast AQMD any increase in emissions from new equipment or a modification will require BACT, but in a more rural district the allowable level will be much higher (i.e. 25 pounds a day). Districts will also have different trigger levels for different pollutants.

403.7.2 Offsets

If emissions from a new or modified source are increased above the levels that require BACT, "offsets" may be required. The level at which offsets are triggered will also depend on the district's air quality designation. When offsets are triggered, the facility must decrease emissions in another area, or "offset" them. This can be done by shutting down equipment, buying emission credits from another source, or by making changes to other equipment to reduce emissions.

500 INSPECTION

Stationary Reciprocating Engines

501 INSPECTION

Sources are inspected in order to verify that a company's equipment is designed, installed, and operating in accordance with air pollution regulations and Permits to Operate. There are four ways that the compliance status of a source can be evaluated:

1. Engineering evaluations
2. Inspections
3. Source testing
4. Continuous emission monitoring

Of these, only the second two provide actual emission data as to the extent of emissions from a facility. Inspections will primarily be the focus of this section, but source testing and continuous emission monitoring shall be briefly discussed.

I&M

One of the best ways a source can stay in compliance with air pollution regulations is through preventative maintenance inspections. Companies that have efficient inspection and maintenance (I&M) programs tend to have fewer breakdowns, require fewer variances, have less down time and can save money. With an efficient I & M program, problems with equipment can be anticipated and surprising catastrophic failures can be reduced. A good I & M program also requires that neat, orderly, consistent records of self-inspections be kept by the company. Local districts can usually assist sources with I & M programs.

Reasons for Inspection

Inspections of facilities may be performed for any one of the following reasons:

1. Compliance determination
2. Complaint investigation as a result of excess emissions or equipment malfunction
3. Source plan approval
4. Review or renewal of Permits
5. Special studies

Examples of special studies would be operating and maintenance evaluations, or updating emission inventories.

Compliance-type inspections only provide preliminary emissions assessments. Source testing is the method of determining compliance with an emission standard. Compliance inspections are usually unannounced so that a facility can be evaluated under normal operating conditions.

For other inspections pertaining to source construction, plan approval, Permits to Operate, or "baseline type" inspections, the plant should be given sufficient advance notice so that qualified plant personnel can be present to provide the drawings, manuals, and process information that may be required. Prior notice should also be given when performing inspections for special studies designed to document operating and maintenance practices, or process and emission data. This will allow the operator time to make readily available information such as raw material rates, production levels, and stack test results. Regardless of the type of inspection to be conducted, pertinent supporting information should be obtained prior to, during, and following the source evaluation.

501.1 SEQUENCE OF INSPECTION

The sequence of an inspection is a question of what order to inspect the equipment in a system. The two main logical sequences to follow are a cocurrent and a countercurrent approach, but regardless of the type of sequence chosen, it is usually best to initially inspect the outside of a facility. By inspecting the perimeter of a plant an inspector can see if there are any illegal emissions or odors before the source is aware of an inspector's presence.

501.1.1 Cocurrent Approach

The inspection of a facility using a cocurrent approach is conducting the inspection in the same general direction as the flow of the gas stream. The general sequence of a cocurrent inspection is the process, the capture system, the control device, and the stack. An inspector may want to use this type of approach when he is unfamiliar with some process details.

501.1.2 Countercurrent Approach

An inspection with a countercurrent sequence is conducted against the direction of gas flow. An inspection of this type would generally begin at the stack and continue to the control device, capture system and then the process. The advantage of this approach is that an inspector may be able to more quickly identify where an emission problem originates.

501.1.3 Other Approaches

In some instances an inspector may not start with the stack of the process or the beginning or end of a system. If odors were detected outside the facility, an inspector may want to head directly to the source of the odor. If an inspector suspects illegal tampering with the control device equipment, he may head there directly. If an inspection is a strict, unannounced compliance-type, or if an inspector is very familiar with the process and only has a particular item to deal with, the inspection could start and finish in a different manner.

501.2 LEVELS OF INSPECTION

Four different levels of inspection have been developed by the USEPA. These levels are classified as 1, 2, 3, or 4, where a level 1 inspection consists of an inspection that is the least in-depth and a level 4 inspection is the most in-depth. The levels are inclusive; a level 3 inspection, for example, would also include all the items done in a level 1 and level 2 inspection. Although these levels may not always be strictly adhered to in practice, the levels help organize all the means in which a system can be inspected.

Visible emissions evaluations are a part of level 1 inspections, and a survey of the plant boundary could be considered a part of a level 1 inspection. In a level 2 inspection an inspector conducts a walkthrough evaluation of the engine and related equipment. All the data acquired in a level 2 inspection is acquired from on-site gauges (Fig. 501.1). In a level 3 inspection, independent measurements of operating conditions separate from the existing on-site gauges are conducted. This is usually done when the existing on-site gauges are inadequate. A level 4 inspection is performed by agency supervisors or senior inspectors to acquire baseline data. As with the level 3 inspection, independent monitoring equipment is used for the level 4 inspection. The "baseline" data acquired in past level 4 inspections is used by inspectors to check the operation of the equipment.

500 INSPECTION

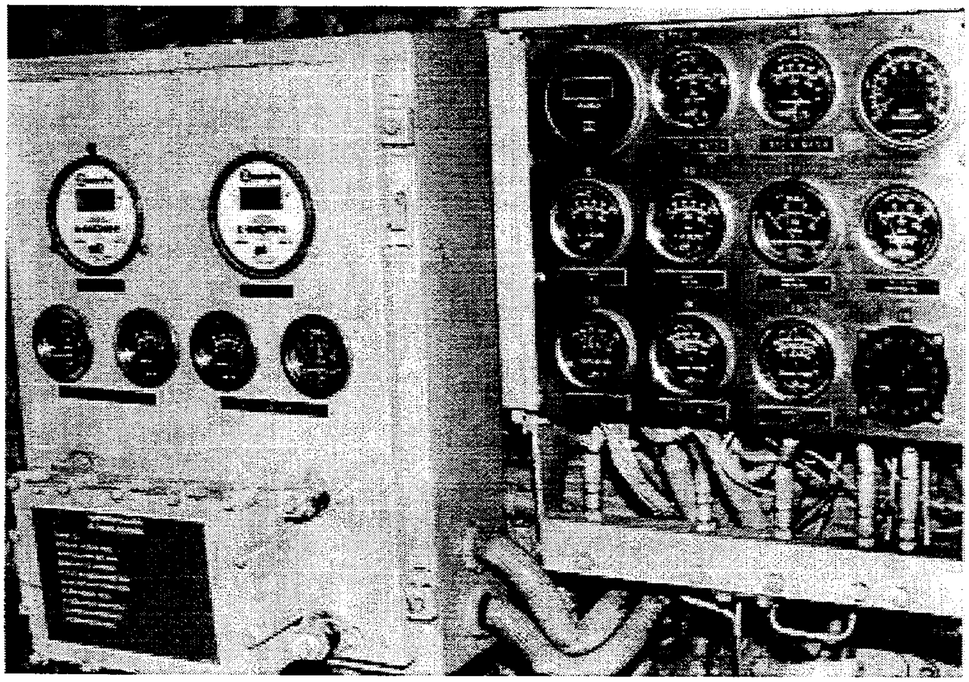

Figure 501.1 Reciprocating Engine Gauges

502 PRE-INSPECTION PROCEDURES

It is important to prepare for the inspection prior to your visit to the facility. Rules and Permits can be very complicated and preparations must be made for a successful inspection. This section is a discussion of some general guidelines on what steps to follow prior to the inspection.

502.1 FILE REVIEW

Prior to the site inspection, the inspector should review all information available in the district source files including: approved Permits, equipment lists, conditions for each Permit, previous inspection reports, Notices of Violation, breakdown reports, enforcement actions taken, odor complaints, variance histories, alternative emissions control plans, abatement orders, source tests, and the design of the plant.

Verify that all applicable Permits for the facility are current and valid. Bring a current copy of the Permit(s) and bring extra copies in case the facility has misplaced or lost their copy.

The inspector may wish to complete some portions of the inspection documentation before arriving at the facility, as this will save time during the pre-inspection meeting. If your district has checklists or rule specific forms, use them.

502.2 REGULATION REVIEW

You should review any references to the specific rules which are noted in the source files. In particular, be familiar with each standard and exemption in the rules. Discuss regulations that apply to the facility with experienced personnel and review any policies your district may have. Make sure that you receive consistent interpretations on how to apply the requirements of rules. Review the most recent version of your district's regulation in its entirety.

502.3 EQUIPMENT CHECK

Make sure that you have the following equipment available for use during the inspection: vision protection, hearing protection, safety shoes, hard hat, gloves, identification, business cards, pens, wipes, inspection forms (see example form, Table 503.1), chain of custody forms, sampling cans, can case, labels, and thermometer.

502.4 PRE-ENTRY AND ENTRY

When you arrive at the plant, notice if there are any visible emissions. If there are any visible emissions, make sure you document them and plan on finding the sources as soon as possible after entering the facility. Make sure you don't confuse steam or water vapor with a pollutant emission.

Request to see the previous contact mentioned in the files. Depending on the facility, it may be the environmental coordinator, supervisor, president, maintenance worker or operator. Always present your business credentials immediately to avoid confusion.

500 INSPECTION

Table 503.1
RECIPROCATING ENGINE INSPECTION FORM

Pre-Inspection:	Field Inspection:
Facility name: Unit I.D. number:	Date/time:
Permit number: Permit expiration date:	Inspector: Agency:
Facility address:	Facility contact person(s)/title(s):
Date unit was built or last modified:	
Manufacturer: Rated horsepower: Lean burn___ Rich burn___ Diesel___ Dual fuel___	Is the same engine still installed?
Type of Emission Control System	
PCV___ Catalytic converter___ type: Two way___Three way___ NSCR___ SCR___ PSC___PCC___	Are the systems operating properly?
Visible Emissions	
Any past problems with visible emissions?	Are there any visible emissions? Result of visible emissions evaluation:
General Physical Conditions	
Any past problems with air pollution related equipment?	Any excessively corroded, or poorly maintained equipment?
Fuels	
What fuel(s) is the engine permitted to burn?	What kind of fuel is the engine burning?
Time of Operation	
How many hours per year are the engines allowed to operate?	Hours of operation since last inspection: Hours of operation this year:
Emission Data from CEMs	
Emission limits: NOx: CO: SOx: Ammonia slip: O2: Particulates:	Emissions according to CEM: NOx: CO: SOx: Ammonia slip: O2: Particulates:

If the source is unfamiliar with your district's authority, be prepared to cite and provide copies of California Health & Safety Code (CHSC) Section 41510: Right of Entry (a copy is available in the Appendix). Know and follow your district's policy if the facility refuses entry.

502.5 PRE-INSPECTION MEETING

Before the inspection begins, the inspector should meet with the source representative to obtain operating information. The inspector should state the purpose of the inspection and identify the equipment which will be inspected. Facility information can be verified during this meeting, including: the facility name and ownership, address complete with city and zip code, contact name, contact title, phone number and area code. Discuss safety procedures and whether or not there have been any problems in the past. Request a copy of applicable material safety data sheets (MSDS). A facility may have over a thousand of them since MSDSs exist for materials ranging from dishwashing soap to ammonia. If necessary discuss sampling procedures with the source representative.

The district's equipment list on the Permit to Operate should be compared to the facility's Permit to Operate. The items should be the same. If they are not, a Notice of Violation may have to be issued. Also, check existing Permit conditions and ask if any other changes have been made to the operation which are not reflected in the Permit.

503 RECIPROCATING ENGINE INSPECTION

Inspectors can determine whether an engine complies with air pollution regulations and Permits to Operate by obtaining operating information and comparing the data to limits on Permits. Source tests must be conducted to determine an engine's emissions, but items in this section discuss how an inspector can determine compliance.

503.1 ENGINE VISIBLE EMISSIONS (ALL LEVELS)

EPA Method 9 (Visual Determination of the Opacity of Emissions from Stationary Sources) is found in 40 CFR Ch. 1, Part 60. The method requires the recording of certain specific information in the field documentation of a visible emission observation. The required information includes the name of the plant, the emission location, the type of facility, the observer's name and affiliation, the date, the time, the estimated distance to the emission location, the approximate wind direction, the estimated wind speed, a description of the sky conditions, and the plume background, in addition to a minimum of 24 observations.

In California the visible emission regulation is in Section 41701 of the California Health and Safety Code. The limit in the Health and Safety Code is a Ringelmann No. 2 or 40% opacity. The Ringelmann chart is a gray to black smoke scale, published by the United States Bureau of Mines, ranging from 0 to 5, where "0" is no visible smoke and "5" is totally black 100% opaque smoke (Table 403.11). In most districts the limit is Ringelmann No.1 or 20% opacity. White or colored smoke is measured by percent opacity. California provides that an aggregate of any of 13 or more readings (totalling more than 3 minutes) taken in a 1-hour period is a violation.

If possible, the visible emissions from the stack should be observed before entering the facility. There should be little or no visible emissions coming from the stack. Only occasional faint wisps of smoke should be visible. If the emissions are over a Ringelmann 1, it is a violation in most districts. Permits may allow visible emissions during startup or shutdown of the stationary engines.

Smoke Reading

Observe the stack for emissions which would violate the opacity or Ringelmann limitations in your district regulations. Remember, you must be certified to do a visible emissions evaluation. A visible emissions evaluation (VEE) kit should be available to the inspector. The kit should include the following:

- VEE Forms
- Binoculars
- Wind gauge
- Stopwatch
- Camera and film
- Pens
- Flashlight
- Range finder--to measure stack distance
- Psychrometer--to calculate relative humidity
- Inclinometer--to measure stack angle of view
- Compass
- Water bottle
- Ringelmann chart

Another potential source of visible emissions violations is smoke from burning lubricating oil. Some engines, especially diesel engines, will smoke when they are first started. However, an engine should not continuously smoke.

503.2 GENERAL PHYSICAL CONDITIONS

As with most inspections, it is good to walk around the equipment at the plant, familiarize yourself with it, and look at the general condition of the equipment. On the other hand, much of the equipment for an engine cannot be physically inspected, especially if it is running. Check for any signs of excessive corrosion, erosion or poor maintenance. Look for cracked or worn ductwork expansion joints. It is unlikely that an engine would have these types of problems, since they could be dangerous and inefficient, but these procedures are good to follow for most inspections.

503.3 RECIPROCATING ENGINE FUELS

Stationary reciprocating engines can burn a variety of fuels ranging from natural gas to distillate oil. Limits stated on the Permit may restrict what fuels can be used in the engine. Permits may also require facilities to measure and record their fuel usage. Acquire a copy of the company's records showing the fuels used and the fuel usage since the last inspection. If any fuel was used that is not on the Permit, it is a violation.

It may be necessary to acquire a sample of the fuel to verify that it complies with the Permit. A major reason for sampling the fuel is to check the sulfur content. Permits may state the maximum allowable sulfur content of the fuel, especially if it is distillate oil. An inspector should have facility personnel acquire samples, so they will not be libel for any damage to the equipment at the facility. Observe the person acquiring the sample to make sure it is gathered properly.

The storage of fuels for engines can be a potential source of emissions. Liquid petroleum fuels are kept in storage tanks. The inspection of storage tanks is included in the Petroleum Refining Technical Manual. In general, depending on the vapor pressure of the product in the tank, the tank and its pressure relief valves cannot leak hydrocarbon emissions. Floating roof tanks must also meet gap limits. Most engines that run on liquid petroleum fuels use fuels with a low vapor pressure, such as diesel, which does not require vapor recovery or a gas tight tank. On the other hand, engines can run on high vapor pressure fuels such as gasoline.

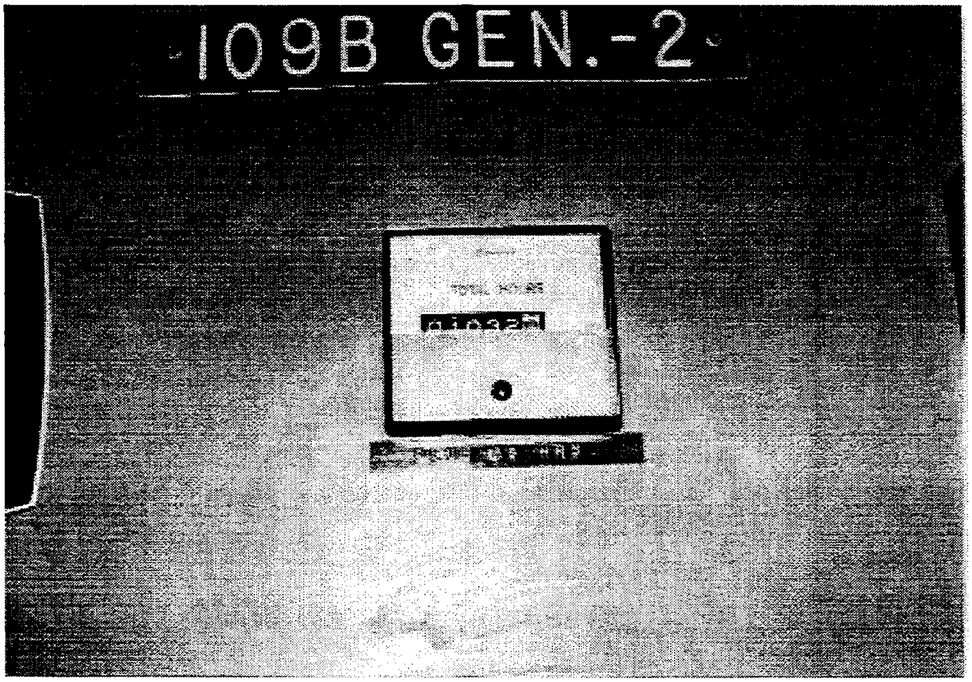

Figure 503.1 Hours Meter

503.4 TIME OF OPERATION

A Permit may have conditions for engines that limit the hours of operation per year. Reciprocating engines are often used for emergency backup power and these engines often have limits on the time of operation. Acquire a copy of the facility's records showing the hours of operation since the last inspection or check the hours meter (Fig. 503.1). Compare the data to the requirements on the Permit and make sure that all engines operated for a period of time that is less than the maximum time allowed.

A Permit may describe the length of time for a startup and a shutdown period. The Permit may allow a facility to exceed maximum emission concentrations stated on the Permit during startup and shutdown. On the other hand, the facility could still be accountable for these emissions on a daily or yearly basis.

503.5 AMMONIA INJECTION AND SCR

The amount of ammonia injected for selective catalytic reduction is an important parameter. If enough ammonia is not injected there will be a lower amount of NOx removed, but if the ammonia injection is excessive, there will be an excessive ammonia slip. In extreme cases a large ammonia slip will cause a yellowish or brown plume.

If engines have SCR, the Permit will typically require that it operates, except during startup and shutdown, whenever the engine operates or when the exhaust gases are above a specific temperature. This temperature is usually relatively low, so that during normal operation it will easily be exceeded. Continuous monitoring and recording of the temperature at the catalyst or other locations will probably be required. Permit conditions will also usually state the maximum concentration of ammonia allowed in the stack gas and require the facility to keep track of ammonia usage. Acquire copies of the company's ammonia usage records. Obtain copies of chart recorder printouts and other necessary data.

503.6 ENGINE EMISSIONS

Permits to Operate for stationary engines may often state daily or hourly emission limits (e.g. lbm/day, gr/hp-hr) and/or concentrations (e.g. ppmv) of NOx, CO, SOx, particulate matter, and hydrocarbons (usually non-methane hydrocarbons). Some engines may be equipped with advanced continuous emission monitors (CEMs) that can measure NOx, CO, SOx, and O_2, and can make logs of the data. Permits will require specific pollutants that a facility must monitor, how often the monitor must sample the emissions (i.e. every fifteen minutes) and how often the CEM must be calibrated. If the facility is equipped with CEMs that measure the emissions, acquire a copy of the records and compare the data to the emission limits that are allowed in the stationary engine rule or Permit to Operate. Even if a facility has continuous emission monitors, periodic source tests must be done to determine the emissions. Continuous emission monitors can yield incorrect emission measurements.

Some facilities may not continuously monitor pollutants such as particulates and unburned hydrocarbons, especially if the engine will burn a light clean fuel. Source tests are usually conducted to determine these emissions and these requirements may be stated on the Permit.

503.7 ENGINE DERATING VERIFICATION

Some districts allow engine derating below 50 Bhp, thereby exempting the engine from the emission limits or emission control requirements. An example method of accomplishing engine derating is by the use of an orifice plate between the carburetor and one intake manifold. The orifice plate reduces the cross-sectional area available for air and fuel to flow into the intake manifold.

504 POST-INSPECTION PROCEDURES

Prior to leaving the facility, the inspector should evaluate the compliance status of the plant and should have obtained all the information necessary to complete the inspection forms.

The facility should be informed of the results of the inspection, advised of areas of concern where additional information or investigation is needed, or given a Notice of Violation (NOV) as soon as possible. Be prepared to make your compliance determinations, calculate excess emissions, and issue all necessary violation notices. Be able to document future NOVs which may be pending due to sample results or additional information requests. **All violations should be followed up**, consistent with your district policy, to ensure that the source is brought into compliance. Always update the Permit file to reflect actions that took place during and as a result of the inspection.

GLOSSARY

Absolute Pressure - The pressure, including the pressure due to the atmosphere. The pressure measured above a vacuum.

Adiabatic - A process where there is no heat transfer.

Aftercooler - A heat exchanger that is used to cool the air flowing through a turbocharger. Water or air is usually used to provide the cooling.

Aldehydes - Compounds emitted from the exhausts of engines formed from partially oxidized hydrocarbons. Once in the atmosphere, they can contribute to eye irritation. Aldehydes can also be formed photochemically.

Alveoli - Small air sacs in the lungs where gas exchange of carbon dioxide and oxygen between the air and the blood takes place.

Ammonia (NH_3) - A hazardous substance (Title III, Section 302, SARA) that is usually used in selective catalytic reduction to remove NOx compounds. It is injected into the flue gas before it flows through the selective catalytic reduction catalyst. Ammonia is also injected into other combustion processes to reduce NOx.

Ammonium Bisulfate - An ammonia salt that forms from ammonia and sulfur trioxide (SO_3). It is a sticky substance that can foul and corrode equipment in the exhaust system.

Ammonium Sulfate - An ammonia salt that forms from ammonia and sulfur trioxide (SO_3). It is a substance that can foul equipment in the exhaust system, but it is not corrosive like ammonia bisulfate.

Ammonia Slip - The unavoidable emissions of ammonia from the stack of a selective catalytic reduction unit. Excess ammonia is required for SCR since mixing is not perfect. Excess and unreacted ammonia becomes the ammonia slip.

Ash - Incombustible material. Ash is a component of a fuel and may flow through a combustion process without being destroyed, becoming particulate matter.

GLOSSARY

Authority to Construct - A document given by an air pollution control district to permit a company to build or modify pollution generating or control equipment.

Autoignition - A condition that occurs in the cylinder of a reciprocating engine where a portion of the fuel charge spontaneously ignites without a separate ignition source. This occurs if the temperature and pressure of that portion of the fuel charge exceeds the self-ignition conditions for the air and fuel mixture being burned.

Best Available Control Technology (BACT) - An emission limitation based on the maximum degree of emission reduction that is achievable and has been demonstrated in practice. In no event does BACT permit emissions in excess of those allowed under any applicable NSPS or NESHAP. It is applicable on a case-by-case basis for each major new (or modified) emission source to be located in nonattainment or attainment areas. It applies to each pollutant regulated under the Federal Clean Air Act, and is concerned with Prevention of Significant Deterioration (PSD).

Best Available Retrofit Control Technology (BARCT) - An emission limitation that is based on the maximum degree of emission reduction achievable while taking into account environmental, energy, and economic impacts. BARCT is used in serious nonattainment areas. BARCT is either equivalent to or less stringent than BACT.

Bottom Dead Center (BDC) - The lower limit of a piston's travel in a cylinder when the cylinder's volume is maximized.

Brake Horsepower - Shaft horsepower or delivered horsepower. Usable energy at the crankshaft of an engine after accounting for friction and pumping losses.

Butane (C_4H_{10}) - A hydrocarbon derived from crude petroleum that is gaseous at atmospheric conditions but is easy to liquefy. It is the lightest hydrocarbon in gasoline.

California Health and Safety Code (CH&SC or H&SC) - A publication containing the state laws and statutes for air pollution control in California.

GLOSSARY

Camshaft - A shaft on which cams are mounted. The camshaft is driven by the crankshaft with belts or chains (also called timing belts or timing chains). As it rotates, the cam actuates (pushes) the follower, which then opens a valve.

Carbon Dioxide (CO_2) - A gaseous product of combustion Carbon dioxide is not considered to be a pollutant, but it is a greenhouse gas.

Carbon Monoxide (CO) - A combustion product formed from incomplete combustion. It is a pollutant that forms when there is not enough oxygen or too much fuel in a combustion process. When inhaled, CO attaches more easily to hemoglobin than does oxygen, reducing the amount of oxygen reaching the body's cells.

Carburetor - A device on a reciprocating engine used to mix air and fuel in the correct ratio. Carburetors were generally used on older engines and are not as precise for mixing fuel and air as fuel injectors.

Catalyst - A substance that hastens or retards a chemical reaction without being changed by the chemical reaction itself.[1]

Catalytic Converter - An emission control method for automotive engines similar to NSCR that uses a catalyst to control carbon monoxide, hydrocarbons, and/or NOx emissions. Carbon monoxide is converted to carbon dioxide, hydrocarbons are converted to carbon dioxide and water, and NOx is reduced to diatomic nitrogen.

Cetane Number - A measure of the ignition quality of diesel fuel. With a higher number the fuel will be more volatile and easier for starting under cold conditions and will smoke less.

Char - Slow-burning organic material. Once char exits a combustion process, it may become particulate matter.

Clearance Volume - The small space left above a piston inside a cylinder at the upper limit of the piston's travel.

Cogeneration - A power plant or engine that produces mechanical work or electricity and steam or hot water. The steam/hot water is sent to another thermal process.

GLOSSARY

Compression Ignition (CI) - An engine that uses the heat of compression to initiate combustion.

Compression Ratio - The volume of a cylinder at bottom-dead-center divided by the volume of the cylinder at top-dead-center in a reciprocating internal combustion engine.

Continuous Emission Monitor - A device that continually measures pollution emissions or process parameters from an operation, engine, or other device. The emissions may be printed on a chart recorder. Carbon monoxide, sulfur dioxide and nitrogen oxides are pollutants often measured in stacks of engines by continuous emission monitors.

Crankcase - The main body of a reciprocating engine. It usually contains the crankshaft and engine oil.

Crankshaft - A shaft to which all the connecting rods and pistons of an engine are connected. It converts the reciprocating motion of the pistons into rotary motion.

Crude Oil - Petroleum that has not been refined. Oil as it comes from an oil well.

Cyanuric Acid $(HNCO)_3$ - A NOx control method where cyanuric acid is exposed to heat, forming isocyanic acid which is injected into the exhaust stream after the turbocharger of an engine.

Cylinder Head - The top of the cylinder. It often has the valves and spark plugs mounted within it.

Density - Mass per unit volume, e.g. lbm/ft^3. The mass of a substance divided by its volume. The reciprocal of specific volume.

Detonation - (also see knock) Any unusual sound (e.g. a ping or a thud) that arises because of autoignition during the normal combustion process. A condition of uncontrolled rapid burning of an air/fuel mixture in a reciprocating engine. Detonation can damage the materials of the engine and will cause it to run poorly.

GLOSSARY

Diesel Cycle - The theoretical combustion cycle of the compression ignition engine. Diesel engines use the heat from compression for combustion; they do not have spark plugs. The parts of the cycle include adiabatic (no heat transfer) compression (in the cylinder from a piston), constant pressure heat addition (combustion), adiabatic expansion (work done on the piston) and constant volume heat rejection to the atmosphere.

Diesel Fuel - A refined petroleum product made from petroleum in the light gas oil range. Gas oil has a boiling point between 450 and 800°F and is heavier than hydrocarbons in the kerosene range.

Digester Gas - A fuel primarily made of methane acquired from the biological treatment of waste water or sewage. When organisms break down wastes during sewage treatment, methane and carbon dioxide are formed.

Displacement - The part of the volume of the cylinders in a reciprocating engine that is encompassed by the piston's travel. In general, the larger the displacement the higher the power output.

Dual Cycle - A theoretical combustion cycle that is a combination of the Otto Cycle (spark ignition engine) and the diesel cycle (compression ignition engine).

Dual Fuel Engine - An compression ignition engine that uses diesel fuel and a supplementary fuel.

Dynamometer - A device used to test the performance of an engine. The dynamometer puts a load on the engine and measures its response to it.

Enthalpy - The total usable energy of a substance. It is often used to gauge the energy of a flow of steam or combustion gases. It is usually has units of Btu/lbm.

Entropy - Energy that is not available to do work. The amount of randomness or disorder of a system. The units of entropy are Btu/lbm-°R.

Equivalence Ratio - (usually defined as the symbol "ϕ") The ratio of the stoichiometric air/fuel ratio to the actual air/fuel ratio. At stoichiometric the equivalence ratio is 1.0. The equivalence ratio is greater than one when rich and less than one when lean. The equivalence ratio is the inverse of the excess air ratio, i.e. $\phi = 1/\lambda$ where "λ" is the excess air ratio.

GLOSSARY

Ethane (C_2H_6) - A gas that comprises a relatively small component of natural gas, but is often the second most common gas in natural gas. Methane is the main gas in natural gas.

Excess Air Ratio - (usually defined as "λ") The excess air ratio is the ratio of the actual air/fuel ratio to the stoichiometric air/fuel ratio. It is 1.0 at stoichiometry, greater than one when lean and less than one when rich. The excess air ratio is the inverse of the equivalence ratio, i.e. $\lambda = 1/\phi$ where "ϕ" is the equivalence ratio.

Exhaust Gas Recirculation - An emission control method that involves recirculating exhaust gases from an engine back into the combustion chamber. This lowers combustion temperatures and reduces NOx.

Exhaust Manifold - An internal passage in an engine that routes exhaust gases from all the cylinders out of the engine.

External Combustion Engine - An engine where a fluid is used to transfer heat from the energy of combustion to a portion of the engine where it is transformed into mechanical energy. An example is a steam engine or a steam power plant.

Flywheel - A large heavy disc or wheel connected to the crankshaft of the engine. The inertia of the flywheel turns the crankshaft so it can coast through the intake, compression, and exhaust strokes.

Follower - A part within many reciprocating engines shaped like a bottle cap which is actuated by the cam when the camshaft rotates.

Friction Horsepower - Energy losses that occur due to friction in bearings and pumping of exhaust gases out of the cylinder. It includes all the energy lost between the piston and crankshaft.

Fuel Bound Nitrogen - Nitrogen that is present in a fuel. Any nitrogen in a fuel can form into NOx compounds when the fuel burns.

Fugitive Emissions - The escape of pollutant emissions into the atmosphere from man-made or natural sources. Some examples include emissions of VOCs from leaking storage tanks, valves, flanges, pumps and compressors at refineries or chemical plants; particulates from storage piles; or natural windblown dust.

GLOSSARY

Gas Turbine - An engine that uses a compressor to draw air into the engine and compress it. Fuel is added to the air and combusted in the pressurized combustor. Hot combustion gases exiting the engine turn a turbine which also turns the compressor. The engine's output power can be received from the compressor or turbine side of the engine.

Gauge Pressure - The pressure indicated on a gauge where a reading of zero is equivalent to atmospheric pressure (14.7 psi). An example is the reading on a tire pressure gauge.

Heat Rate - A parameter which is equivalent to the total energy output of a process (such as a power plant or engine) in Btu/hr divided by the energy output in kilowatts. The units of heat rate are therefore usually Btu/kilowatt-hr.

Hemoglobin - An oxygen carrying protein that is in the red blood cells. Hemoglobin carries oxygen from the lungs to all the cells throughout the body. Carbon monoxide attaches more strongly to hemoglobin than oxygen. This is why emissions of carbon monoxide are a great concern.

Heterogeneous Nucleation - A particle formation mechanism where solid material nucleates or accumulates on the surfaces of previously formed particles. The temperature must be below the dew point temperature of the material for heterogeneous nucleation to occur.

Higher Heating Value (HHV) - The heat released by burning a particular fuel. The higher heating value includes the heat necessary to vaporize the water formed from combustion.

Homogeneous Nucleation - A particle formation mechanism where vapor phase material condenses to form new particles. The temperature must be below the dew point temperature of the material for homogeneous nucleation to occur.

Horsepower - A measurement of power equivalent to 550 ft-lbf/sec.

Hydrocarbons - Organic compounds of hydrogen and carbon atoms. There is a vast number of these compounds. Some examples include: methane, butane, heptane, octane, benzene, etc. Emissions of volatile hydrocarbons into the atmosphere can lead to the formation of smog in the atmosphere.

GLOSSARY

Hydrogen Sulfide (H_2S) - An odorous, poisonous, unwanted gas that is encountered in many gas production, oil production, and refining operations. It has a strong rotten egg odor, but it cannot be detected by a person's sense of smell at high concentrations.

Immediately Dangerous to Life and Health (IDLH) - A concentration of a chemical, as published by the National Institute for Occupational Safety and Health (NIOSH), that would be immediately dangerous to a person's health and safety upon exposure.

Incomplete Combustion - The burning of fuel and air where the fuel is not completely burned. Incomplete combustion can be caused by too little air or too much fuel in a combustion process. Incomplete combustion results in carbon monoxide emissions.

Indicated Horsepower - The energy from burning a fuel in a reciprocating engine that is utilized in pushing the piston(s) down the cylinder(s). It does not include the heat lost through the cylinder walls.

Indicator Card - An actual plot of pressure versus volume within a cylinder of a reciprocating engine.

Intake Manifold - An internal passage within an engine that directs air and fuel to all the cylinders.

Intercooler - A heat exchanger that is used to cool the air flowing through a two stage turbocharger. Water or air is usually used to provide the cooling.

Internal Energy - All the kinetic and potential energy in the atoms and molecules of a substance. Internal energy is usually in units of Btu/lbm.

Internal Combustion Engine - An engine that uses air from the atmosphere and combustion of the fuel and air occurs in or near a portion of the engine where the energy of combustion is converted into mechanical energy. Examples are gas turbines and reciprocating engines.

Isentropic - A process where the entropy (the amount of energy not available to do work) is constant. A reversible, adiabatic (no heat transfer) process.

GLOSSARY

Kerosene - A refined fraction of crude petroleum that is heavier than naphtha, but lighter than gas oil. It has a boiling point between 315 and 450°F.

Kinetic Energy - The energy possessed by an object in motion. Kinetic energy is one-half times the mass of the object, times the velocity squared. A gas or a liquid in motion also has kinetic energy.

Knock - (also see detonation) Any unusual sound, e.g. a ping or a thud that arises because of autoignition during the normal combustion process. A condition of uncontrolled rapid burning of an air/fuel mixture in a reciprocating engine. If knocking is severe, it can damage the engine and will cause it to run poorly.

Landfill Gas - A gaseous fuel primarily made of methane and carbon dioxide that is acquired from a landfill. In general, landfill gas has relative low emissions when burned in an engine.

Lean - An air-fuel mixture that has more air relative to fuel compared to the amount of air and fuel at stoichiometric.

Lean Burn Engine - An engine that has more than 4% oxygen in its exhaust.

Lower Explosive Limit (LEL) - The lowest concentration at which a mixture of air and volatile compounds becomes flammable.

Lower Heating Value (LHV) - The heat released when burning a fuel. The lower heating value does not include the heat necessary to vaporize the water produced from combustion, but the higher heating value does.

Manometer - A device used to measure the relative or gage pressure inside a vessel. A manometer has a glass tube that contains water or mercury, measuring the pressure in inches of water or mercury.

Masking - A process where particulates, ammonia salts, and other contaminants in the exhaust of an engine coat a catalyst in a SCR system or other unit, decreasing its ability to control emissions.

Mean Effective Pressure - A mean value of pressure in the cylinder of an engine such that when it is multiplied by the displacement it yields the work output.[2]

GLOSSARY

Methane (CH_4) - A gaseous fuel that makes up most of natural gas, landfill gas and digester gas. Methane is a greenhouse gas.

Micrometer (micron) - A unit of length, the thousandth part of 1mm or the millionth (10^{-6}) of a meter (approximately 1/25,000 of an inch).

Molecular Weight - The relative weight of atoms or molecules. The weight of one mole of atoms or molecules, one mole being 6.02×10^{23} individual atoms or molecules. The molecular weight of carbon, for example, is 12.

Multiple Pump Injector - An fuel injector for a diesel engine where the fuel pumps are separate from the injector. It injects fuel at very high pressures.

National Ambient Air Quality Standards (NAAS) - Specified concentrations and durations of air pollutants determined by EPA pursuant to Section 109 of the Federal Clean Air Act. NAAQS exist for nitrogen oxides, sulfur oxides, particulate matter, ozone, and carbon monoxide.

National Emission Standards for Hazardous Air Pollutants (NESHAPS) - Federal standards for the emissions of toxic compounds.

Natural Gas - Gaseous hydrocarbons made of at least 80% methane and maybe some ethane, propane, and butane.

New Source Performance Standards (NSPS) - Federal regulations from the EPA for new or modified stationary sources. They are located in the Code of Federal Regulations Title 40 Part 60.

Nitrogen Oxides (NOx) - A compound of a nitrogen atom and one or more oxygen atoms. These compounds are emissions of combustion processes and can lead to ozone formation (examples: NO = nitrogen oxide; NO_2 = nitrogen dioxide). Most of the NOx from combustion processes is in the form of NO, but NO later forms into NO_2. NO_2 is much more harmful than NO. Nitrous Oxide (N_2O) emissions can also be a concern, but they are a much smaller problem.

Non-Selective Catalytic Reduction (NSCR) - An emission control technique that involves using one or two catalysts to control carbon monoxide, hydrocarbons, and NOx. Carbon monoxide is converted to carbon dioxide, hydrocarbons are converted to carbon dioxide and water and NOx is converted to diatomic nitrogen.

GLOSSARY

Normally Aspirated - An engine that uses the vacuum within the cylinders from the movement of the piston to draw in air. An engine that does not have a turbocharger, supercharger, or any other means to pressurize air entering an engine.

Notice of Violation (NOV) - Document issued to a company for violating air pollution regulations.

Octane Number - A measure of gasoline's resistance to knock. The higher the number the more resistant the fuel is to knocking. Knocking occurs when a portion of the fuel charge spontaneously ignites without a separate ignition source.

Opacity - The transmissivity of a plume. A perfectly clear plume (100% light transmission) has zero opacity. A plume that transmits no light at all has 100% opacity.

Organic - Of or containing carbon.

Otto Cycle - The theoretical combustion cycle of the spark ignition engine. The parts of the cycle include adiabatic (no heat transfer) compression (in the cylinder from a piston), constant volume heat addition (combustion), adiabatic expansion (work done on the piston) and constant volume heat rejection to the atmosphere.

Oxidation - The process of adding oxygen to a compound. Burning a compound.

Ozone (O_3) - A colorless, odorless gas, formed by chemical reactions between hydrocarbons, nitrogen oxides and sunlight, that is irritating and damaging to humans, plants and animals. It is the main component of smog and is California's biggest air pollution problem.

Partial Pressure - The pressure of a gas in a mixture of gases that would be exerted if the gas was by itself.

Particulates - Solid or liquid particles in the air. Smoke, for example, contains particulate matter. Particulates less than 10^{-6} m (meters) in diameter are also called PM10. Particles of this size and smaller are of greatest concern because they can easily pass deep into the lungs.

GLOSSARY

Permit to Operate - A document issued to the owner or operator of pollution generating or control equipment, allowing the owner to use the equipment in a manner to reduce emissions.

Petroleum - Crude oil as it comes from an oil well. Any of the solid, liquid or gaseous hydrocarbons derived from crude oil.

Photochemical - Chemical reactions that are dependent on the energy of sunlight. Ozone, for example, is a photochemical pollutant and needs sunlight to form.

Piston Rings - Metal rings that are used to seal the gap between a piston and the cylinder (compression rings) and to keep oil out of the combustion chamber (oil scraper rings).

Positive Crankcase Ventilation (PCV) - An emission control system that involves recirculating blowby gases that escape past the piston rings in an engine back into the intake manifold so they can be oxidized.

Power - The rate of doing work. Work over a time period.

Power Derate - Decreasing the power of an engine. This can be used to reduce emissions.

Prechamber - A small chamber where a relatively rich mixture of air and fuel is injected in order to start combustion within a reciprocating engine. When ignition starts the flame travels through holes in the prechamber so the relatively lean mixture in the main combustion chamber can burn.

Preignition - Premature ignition. Combustion that starts from a hot spot in the combustion chamber before normal ignition occurs.

Prestratified Charge (PSC) - A NOx emission control method that involves using a layered or stratified charge in the combustion chamber of an engine. A richer mixture is created near the spark plug while a leaner mixture is created elsewhere. The richer area provides easy ignition and the leaner area provides low emissions.

Prevention of Significant Deterioration (PSD) - A program designed to prevent the deterioration of air quality, especially in areas in attainment.

GLOSSARY

Prompt NOx - A NOx formation mechanism where NOx is formed in the flames of combustion from hydrocarbons formed during intermediate chemical reactions.

Propane (C_3H_8) - A fuel that is derived from petroleum that is gaseous at atmospheric conditions, but it is easily liquefied. Propane is also liquefied petroleum gas (LPG), which is an alternative fuel.

Psychrometer - A device used to measure dry bulb and wet bulb temperature to determine relative humidity. It has two thermometers and a handle that allows a person to twirl the device in a rotational motion. The dry bulb thermometer looks like an ordinary thermometer, but the wet bulb thermometer has a gauze on the end. When a wet bulb measurement is taken, the gauze is wetted and the psychrometer is twirled.

Psychrometric Chart - A chart with a graphical representation of air and water vapor that contains the following parameters: dry bulb temperature, wet bulb temperature, specific volume, enthalpy, relative humidity, and humidity ratio. Once two parameters are known the others can be determined.

Pushrod - A rod that transmits the motion from actuation by a cam to a rocker arm in order to open a valve on a reciprocating engine.

Reactive Organic Gases (ROG) - (ARB definition) Compounds of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate (total organic gases, or TOG). ROG also **excludes** methane, ethane, acetone, and a number of other halogenated hydrocarbons (see complete definition/list in Appendix C).

Reasonably Available Control Technology (RACT) - A level of emission control using demonstrated control technology. RACT is used for moderate nonattainment areas.

Reciprocating Internal Combustion Engine - An engine that consists of pistons in cylinders where air and fuel are introduced into the cylinders, compressed by the pistons, and ignited by a spark plug or the heat of compression. The hot gases from combustion in the cylinders push on the pistons and that energy is transferred to the crankshaft, causing it to rotate.

GLOSSARY

Relative Humidity - The ratio of the absolute humidity in a gas to that of the saturated gas at the same temperature.

Residence Time - The amount of time that fuel and air are within a combustion chamber. This is the amount of time that the fuel and air have to burn.

Rich - An air-fuel mixture that has more fuel than air relative to the amounts of fuel and air at stoichiometric.

Rich Burn Engine - An engine that has less than 4% oxygen in the exhaust gas.

Ringelmann Chart - A gray to black smoke scale published by the U.S. Bureau of Mines ranging from 0 to 5, where "5" is black smoke with 100% opacity, "4" is 80% opacity, "3" is 60% opacity, "2" is 40% opacity, and "1" is 20% opacity. "1" is the limit in most districts.

Scavenging - The process of removing exhaust gases from the cylinder of a two stroke engine and filling it with fresh air.

Scouring - A condition that can adversely affect a catalyst bed, caused by the movement of the hot gas stream wearing down the catalyst over time. The catalyst is sometimes in the form of a coating, so once it wears off, parts of the bed may become useless. This is especially a problem in incinerators.

Selective Catalytic Reduction (SCR) - A popular method of controlling NOx compounds in combustion processes. SCR involves injecting ammonia into the exhaust gas before it flows through a catalyst. The catalysts for SCR can be very large and are often made with a type of noble metal. NOx compounds are converted to nitrogen and water by SCR.

Smog - A combination of the word "smoke" and "fog." Pollutants such as ozone, carbon monoxide, particulate matter, nitrogen oxides, and sulfur oxides make up smog.

Smoke - Small gas-borne particles usually resulting from incomplete combustion. Such particles consist predominantly of carbon and other combustible material and are present in sufficient quantity to be observable independently of other solids.

GLOSSARY

Soot - An agglomeration of carbon particles impregnated with "tar" formed by the incomplete combustion of carbonaceous material. These particles, which are much larger than those constituting a true smoke, are highly visible to the naked eye.

Source - Any building, structure, facility, machine or piece of equipment which is capable of discharging air pollutants.

Source Test - A test performed on pollution generating or control equipment to determine the emissions from it. Source tests have to be conducted on equipment with or without continuous emission monitors to determine the emissions.

Space Velocity - A parameter which is the combined volume flow rate of the inlet gas stream into the catalyst bed of a selective catalytic reduction unit or other device divided by the volume of the catalyst bed. The space velocity is the reciprocal of the residence time.

Spark Ignition (SI) - An engine that uses a spark plug to initiate a spark for combustion in a reciprocating engine.

Spark Plug - A device used initiate a spark in an engine to start combustion.

Specific Fuel Consumption - The mass flow rate of fuel used by an engine divided by its horsepower.

Specific Heat - The ratio of heat to temperature change of a substance. It is the heat transfer divided by the mass of the substance and the change in temperature or $c = Q/m\Delta T$.[3]

where:
c = Specific Heat (Btu/lbm°R)
Q = Heat transfer (Btu)
m = Mass (lbm)
ΔT = Temperature Change (degrees Rankine)

Specific Volume - The reciprocal of density. The volume of a substance divided by its mass.

GLOSSARY

Squish Gap - See clearance volume.

Standard Temperature and Pressure (STP) - A method used to standardize the pressure and temperature between different systems. STP is defined as one atmosphere of pressure at a temperature of 32, 60, 68, or 70 degrees Fahrenheit.

State Implementation Plan (SIP) - A plan that must be delivered to the federal EPA describing how the state will run its air quality programs in order to attain the National Ambient Air Quality Standards.

Stoichiometric - A situation in combustion where there are exactly enough oxygen molecules to react with the fuel molecules. Combustion processes are usually run with excess oxygen (air), since mixing of fuel and air is not perfect and all the oxygen molecules cannot find fuel molecules to react with during the short time period of combustion.

Static Pressure - The pressure exerted by stationary air. The pressure energy of a fluid. Static pressure is usually measured in inches of water column.

Sulfur Dioxide (SO_2) - A pollutant that comes from combustion processes using fuels with sulfur in them, and other industrial operations. It has a sharp, pungent smell.

Sulfur Oxides (SOx) - Sulfur compounds SO_2, SO_3, etc. See "sulfur dioxide."

Supercharger - A system that has a compressor used to draw more air into an engine in order to increase the power output. The compressor is driven by belts, chains, or gears from the crankshaft.

Synergistic Effect - When the combined health effects of more than one pollutant or substance are worse than the effect of the pollutants by themselves. Sulfur dioxide, for example, has worse health effects when it is combined with particulate matter. Sulfur dioxide health effects are even worse when combined with moisture.

Thermal Aging - The gradual recrystallization of noble metal catalyst materials caused by the high temperatures that the catalyst bed is continually exposed to. It is an unavoidable gradual deterioration of the catalyst.

GLOSSARY

Thermal Barrier Coating - A coating applied to the internal parts of a reciprocating engine to protect the parts from high temperature corrosion and thermal shock. Since more heat is kept in the engine, combustion is more complete and emissions of carbon monoxide and hydrocarbons are reduced.

Thermal Burnout - The volatilization of the compounds from the catalyst bed that make up a catalyst. It is caused by excessively high temperatures. This problem occurs in incinerators and other control devices with catalysts.

Thermal Efficiency - The output work of a system or engine divided by the supplied energy (output work/input energy). It is essentially a measure of fuel economy.

Thermal NOx - Nitrogen oxides formed from the nitrogen present in atmospheric air. At higher combustion temperatures, the nitrogen in the air will react (burn).

Title V - A federal EPA operating permit program to track emissions from large sources. Sources with more than 100 tons/year of emissions or 10 tons/year of hazardous pollutants are subject to Title V.

Top Dead Center (TDC) - The upper limit of a piston's travel.

Total Organic Gases (TOG) - (ARB definition) Compounds of carbon, **excluding** carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate.

Toxic Air Contaminant (TAC) - As defined in California Health and Safety Code Section 39655, an air pollutant which may cause or contribute to an increase in mortality or an increase in serious illness, or which may pose a present or potential hazard to human health.

Turbocharger - A device that consists of a turbine connected to a compressor where the turbine is driven by exhaust gases. The turbine drives the compressor and draws more air into the engine, increasing its power output.

Two Stroke Engine - A reciprocating engine that has one power stroke for every time the piston moves from the bottom of its travel to the top and back again.

GLOSSARY

Unit Injector - A fuel injector for a diesel engine that is actuated mechanically by a cam.

Urea Injection - A NOx control method that involves injecting urea and water into the exhaust stream of a combustion process. Supplemental fuel firing must be applied to the exhaust stream.

Vapor Lock - A condition that may occur during hot weather conditions where vapor gets into the fuel lines of an engine. The fuel pump, which is designed to pump liquid, is then unable to send fuel to the engine.

Vapor Pressure - The pressure exerted by a vapor that is in equilibrium with its liquid state.

Variance - Permission given to a facility by an APCD or AQMD to legally pollute beyond regulated limits because of a breakdown or other condition.

Velocity Pressure - The pressure exerted due to the motion of an air stream.

Volatile - A substance that evaporates at a high rate at a low temperature.

Volatile Organic Compounds (VOC) - (USEPA definition) Any compound of carbon, **excluding** carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate, which participates in atmospheric photochemical reactions. VOCs include any such organic compound **other than** the following, which have been determined to have negligible photochemical reactivity: methane, ethane, acetone, methyl acetate, some methylated siloxanes, and a number of halogenated hydrocarbons (see complete definition/list in Appendix C).

Volumetric Efficiency - A measure of how well air is getting into an engine. Increasing it generally increases power output. It is equivalent to the actual mass of air drawn into an engine divided by the theoretical mass of air that should be drawn into the engine.

Wet Bulb Temperature - The temperature indicated by a wet bulb thermometer on a psychrometer. The temperature of atmospheric air that has gone through an adiabatic saturation process (adiabatic means no heat transfer). Adiabatic saturation is the process that occurs when a psychrometer is twirled, causing the water in the gauze of the wet bulb thermometer to evaporate. The energy of evaporation comes from the atmospheric air.

Wrist Pin - A cylindrically shaped pin on the bottom side of a piston through which the connecting rod attaches to a piston.

Zeldovich Mechanism - The chemical reactions that produce NOx compounds.

Zeolites - A type of catalyst that is very porous, able to handle high temperatures, and produces little sulfur trioxide.

APPENDIX A

REFERENCES

100 INTRODUCTION

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200 THEORY AND OPERATION

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CALIFORNIA HEALTH AND SAFETY CODE

The following California Health and Safety Code (H&SC) references are included to demonstrate the authority of district air pollution control districts to adopt regulations, issue permit conditions, perform inspections and pursue enforcement action. Please note that **these regulations are subject to change** and the reader is cautioned to **refer to the current version of the H&SC** when necessary. The relevant Health and Safety Code Sections are presented in numerical order:

39000	Legislative Findings - Environment
39001	Legislative Findings - Agency Coordination
39002	Local and State Agency Responsibilities
39003	ARB Responsibilities
40000	Local/State Responsibilities
40001	Adoption and Enforcement of Rules and Regulations
40702	Adoption of Rules and Regulations
40823	Hearing Board Shall Serve 10 Days Notice
40824	Reasonable Notice for Interim Variance
40825	10 Day Notice for Variances up to 90 Days
40826	30 Day Notice for Regular Variances
41509	No Limitation on Power to Abate Nuisance
41510	Right of Entry With Inspection Warrant
41700	No Person Shall Discharge Pollutants (Public Nuisance)
41701	No Emissions Shall Exceed Ringelmann 2 (Ringelmann/ Opacity Standards)
42300	District Permit System
42301	Requirements For Permit Issuance
42303	Air Contaminant Discharge: Information Disclosure
42303.5	False Statements in Permit Applications
42304	Permit Suspension (Failure to Supply Information)
42350	Applications for Variance
42351	Interim Variance Applications
42351.5	Interim Authorization of Schedule Modification
42352	Findings Required for Issuance of Variance
42353	Other Requirements for Specified Industry, Business, Activity or Individuals
42354	Wide Discretion in Prescribing Requirements
42355	Hearing Board Bond Requirements
42356	Hearing Board Variance Modification or Revocation

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42357	Hearing Board Review of Schedule of Increments of Progress or Final Compliance Date
42358	Effective Period of Order, Final Compliance Date
42359	Public Hearing Requirements; Emergency Exceptions
42359.5	Emergency Variances
42360	Copy of Variance Orders to ARB
42361	Validity of Variance Time
42362	Variance Revocation or Modification
42363	ARB Hearing Prior to Action
42364	Schedule of Fees
42400	General Violations, Criminal
42400.1	Negligence, Criminal
42400.2	Document Falsification or Failure to Take Corrective Action, Criminal
42400.3	Willfully and Intentionally Emitting an Air Contaminant
42401	Violating Order of Abatement, Civil
42402	General Violations, Civil
42402.1	Negligence or Actual Injury, Civil
42402.2	Document Falsification or Failure to Take Corrective Action, Civil
42402.3	Civil Penalties
42402.5	Administrative Penalties
42403	Recovery of Civil Penalties
42404.5	Statute of Limitations for Civil Actions
42450	Orders of Abatement: District Board; Authority; Notice and Hearing
42700	Monitoring Devices: Legislative Findings & Declarations
42701	Determination of Availability, Technological Feasibility, and Economic Reasonableness
42702	Specification of Types of Stationary Sources, Processes and Contaminants
42703	Reimbursement for Actual Testing Expenses
42704	Determination of Availability; Revocation or Suspension
42705	Records
42706	Report of Violation of Emission Standard
42707	Inspection; Fees
42708	Powers of Local or Regional Authority

39000 LEGISLATIVE FINDINGS - ENVIRONMENT

The Legislature finds and declares that the people of the State of California have a primary interest in the quality of the physical environment in which they live, and that this physical environment is being degraded by the waste and refuse of civilization polluting the atmosphere, thereby creating a situation which is detrimental to the health, safety, welfare, and sense of well-being of the people of California.

39001 AGENCY COORDINATION

The Legislature, therefore, declares that this public interest shall be safeguarded by an intensive, coordinated state, regional, and local effort to protect and enhance the ambient air quality of the state. Since air pollution knows no political boundaries, the Legislature declares that a regional approach to the problem should be encouraged whenever possible and, to this end, the state is divided into air basins. The state should provide incentives for such regional strategies, respecting, when necessary, existing political boundaries.

39002 LOCAL AND STATE RESPONSIBILITIES

Local and regional authorities have the primary responsibility for control of air pollution from all sources other than vehicular sources. The control of vehicular sources, except as otherwise provided in this division, shall be the responsibility of the State Air Resources Board. Except as otherwise provided in this division, including, but not limited to, Sections 41809, 41810, and 41904, local and regional authorities may establish stricter standards than those set by law or by the state board for nonvehicular sources. However, the state board shall, after holding public hearings as required in this division, undertake control activities in any area wherein it determines that the local or regional authority has failed to meet the responsibilities given to it by this division or by any other provision of law.

39003 ARB RESPONSIBILITIES

The State Air Resources Board is the state agency charged with coordinating efforts to attain and maintain ambient air quality standards, to conduct research into the causes of and solution to air pollution, and to systematically attack the serious problem caused by motor vehicles, which is the major source of air pollution in many areas of the state.

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40000 LOCAL/STATE RESPONSIBILITIES

The Legislature finds and declares that local and regional authorities have the primary responsibility for control of air pollution from all sources, other than emissions from motor vehicles. The control of emissions from motor vehicles, except as otherwise provided in this division, shall be the responsibility of the state board.

40001 ADOPTION OF REGULATIONS

(a) Subject to the powers and duties of the state board, the districts shall adopt and enforce rules and regulations to achieve and maintain the state and federal ambient air quality standards in all areas affected by emission sources under their jurisdiction, and shall enforce all applicable provisions of state and federal law.

(b) The district rules and regulations may, and at the request of the state board shall, provide for the prevention and abatement of air pollution episodes which, at intervals, cause discomfort or health risks to, or damage to the property of, a significant number of persons or class of persons.

(c) Prior to adopting any rule or regulation to reduce criteria pollutants, a district shall determine that there is a problem that the proposed rule or regulation will alleviate and that the rule or regulation will promote the attainment or maintenance of state or federal ambient air quality standards.

(d) (1) The district rules and regulations shall include a process to approve alternative methods of complying with emission control requirements that provide equivalent emission reductions, emissions monitoring, or recordkeeping.

(2) A district shall allow the implementation of alternative methods of emission reduction, emissions monitoring, or recordkeeping if a facility demonstrates to the satisfaction of the district that those alternative methods will provide equivalent performance. Any alternative method of emission reduction, emissions monitoring, or recordkeeping proposed by the facility shall not violate other provisions of law.

(3) If a district rule specifies an emission limit for a facility or system, the district shall not set operational or effectiveness requirements for any specific emission control equipment operating on a facility or system under that

limit. Any alternative method of emission reduction, emissions monitoring, or recordkeeping proposed by the facility shall include the necessary operational and effectiveness measurement elements that can be included as permit conditions by the district to ensure compliance with, and enforcement of, the equivalent performance requirements of paragraphs (1) and (2). Nothing in this subdivision limits the district's authority to inspect a facility's equipment or records to ensure operational compliance. This paragraph shall apply to existing rules and facilities operating under those rules.

40702 ADOPTION OF RULES AND REGULATIONS

A district shall adopt rules and regulations and do such acts as may be necessary or proper to execute the powers and duties granted to, and imposed upon, the district by this division and other statutory provisions. No order, rule, or regulation of any district shall, however, specify the design of equipment, type of construction, or particular method to be used in reducing the release of air contaminants from railroad locomotives.

40823 HEARINGS - 10 DAYS NOTICE

(a) Except as otherwise provided in Sections 40824, 40825, and 40826, a hearing board shall serve a notice of the time and place of a hearing upon the district air pollution control officer, and upon the applicant or permittee affected, not less than 10 days prior to such hearing.

(b) Except as otherwise provided in Sections 40824, 40825, and 40826, the hearing board shall also send notice of the hearing to every person who requests such notice and obtain publication of such notice in at least one daily newspaper of general circulation within the district. The notice shall state the time and place of the hearing and such other information as may be necessary to reasonably apprise the people within the district of the nature and purpose of the meeting.

40824 REASONABLE NOTICE - INTERIM VARIANCE

In case of a hearing to consider an application for an interim variance, as authorized under Section 42351:

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(a) The hearing board shall serve reasonable notice of the time and place of the hearing upon the district air pollution control officer and upon the applicant.

(b) Subdivision (b) of Section 40823 shall not apply.

(c) In districts with a population of less than 750,000, the chairperson of the hearing board, or any other member of the hearing board designated by the board, may hear an application for an interim variance. If any member of the public contests a decision made by a single member of the hearing board, the application shall be reheard by the full hearing board within 10 days of the decision.

40825 10 DAY NOTICE - 90 DAY VARIANCES

In case of a hearing to consider an application for a variance, or a series of variances, to be in effect for a period of not more than 90 days, or an application for modification of a schedule of increments of progress:

(a) The hearing board shall serve a notice of the time and place of a hearing to grant such a variance or modification upon the air pollution control officer, all other districts within the air basin, the state board, the Environmental Protection Agency, and upon the applicant or permittee, not less than 10 days prior to such hearing.

(b) Subdivision (b) of Section 40823 shall not apply.

(c) In districts with a population of less than 750,000, the chairman of the hearing board, or any other member of the hearing board designated by the board, may hear such an application. If any member of the public contests a decision made by a single member of the hearing board, the application shall be reheard by the full hearing board within 10 days of the decision.

40826 30 DAY NOTICE - REGULAR VARIANCES

In case of a hearing to consider an application for a variance, other than an interim variance or a 90-day variance, or an application for a modification of a final compliance date in a variance previously granted, the notice requirements for the hearing shall be as follows:

(a) The hearing board shall serve a notice of the time and place of a hearing to grant a variance upon the air pollution control officer, all other districts within the air basin, the state board, the Environmental Protection Agency, and upon the applicant or permittee, not less than 30 days prior to the hearing, except as provided in subdivision (d).

(b) The hearing board shall also publish a notice of the hearing in at least one daily newspaper of general circulation in the district, and shall send the notice to every person who requests the notice, not less than 30 days prior to the hearing, except as provided in subdivision (d).

(c) The notice shall state the time and place of the hearing; the time when, commencing not less than 30 days, or, under subdivision (d), not less than 15 days, prior to the hearing, and place where the application, including any proposed conditions or schedule of increments of progress, is available for public inspection; and any other information that may be necessary to reasonably apprise the people within the district of the nature and purpose of the meeting.

(d) In districts with a population of 750,000 or less, the hearing board shall serve, publish, and send the notice pursuant to subdivisions (a) and (b) not less than 15 days prior to the hearing.

41509 POWER TO ABATE NUISANCE

No provision of this division, or of any order, rule, or regulation of the state board or of any district, is a limitation on:

(a) The power of any local or regional authority to declare, prohibit, or abate nuisances.

(b) The power of the Attorney General, at the request of a local or regional authority, the state board, or upon his own motion, to bring an action in the name of the people of the State of California to enjoin any pollution or nuisance.

(c) The power of a state agency in the enforcement or administration of any provision of law which it is specifically permitted or required to enforce or administer.

(d) The right of any person to maintain at any time any appropriate action for relief against any private nuisance.

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41510 RIGHT OF ENTRY

For the purpose of enforcing or administering any state or local law, order, regulation, or rule relating to air pollution, the executive officer of the state board or any air pollution control officer having jurisdiction, or an authorized representative of such officer, upon presentation of his credentials or, if necessary under the circumstances, after obtaining an inspection warrant pursuant to Title 13 (commencing with Section 1822.50), Part 3 of the Code of Civil Procedure, shall have the right of entry to any premises on which an air pollution emission source is located for the purpose of inspecting such source, including securing samples of emissions therefrom, or any records required to be maintained in connection therewith by the state board or any district.

41700 PUBLIC NUISANCE

Except as otherwise provided in Section 41705, no person shall discharge from any source whatsoever such quantities of air contaminants or other material which cause injury, detriment, nuisance, or annoyance to any considerable number of persons or to the public, or which endanger the comfort, repose, health, or safety of any such persons or the public, or which cause, or have a natural tendency to cause, injury or damage to business or property.

41701 RINGELMANN / OPACITY STANDARDS

Except as otherwise provided in Section 41704, or Article 2 (commencing with Section 41800) of this chapter other than Section 41812, or Article 2 (commencing with Section 42350) of Chapter 4, no person shall discharge into the atmosphere from any source whatsoever any air contaminant, other than uncombined water vapor, for a period or periods aggregating more than three minutes in any one hour which is:

(a) As dark or darker in shade as that designated as No. 2 on the Ringelmann Chart, as published by the United States Bureau of Mines, or

(b) Of such opacity as to obscure an observer's view to a degree equal to or greater than does smoke described in subdivision (a).

42300 DISTRICT PERMIT SYSTEM

(a) Every district board may establish, by regulation, a permit system that requires, except as otherwise provided in Section 42310, that before any person builds, erects, alters, replaces, operates, or uses any article, machine, equipment, or other contrivance which may cause the issuance of air contaminants, the person obtain a permit to do so from the air pollution control officer of the district.

(b) The regulations may provide that a permit shall be valid only for a specified period. However, the expiration date of any permit shall be eligible for extension upon completion of the annual review required pursuant to subdivision (e) of Section 42301 and payment of the fees required pursuant to Section 42311, unless the air pollution control officer or the hearing board has initiated action to suspend or revoke the permit pursuant to Section 42304, 42307, or 42309, that action has resulted in a final determination by the officer or the board to suspend or revoke the permit, and all appeals have been exhausted or the time for appeals from that final determination has been exhausted.
(c) The annual extension of a permit's expiration date pursuant to subdivision (b) does not constitute permit issuance, renewal, reopening, amendment, or any other action subject to the requirements specified in Title V.

42301 REQUIREMENTS FOR PERMIT ISSUANCE

A permit system established pursuant to Section 42300 shall do all of the following:

(a) Ensure that the article, machine, equipment, or contrivance for which the permit was issued does not prevent or interfere with the attainment or maintenance of any applicable air quality standard.

(b) Prohibit the issuance of a permit unless the air pollution control officer is satisfied, on the basis of criteria adopted by the district board, that the article, machine, equipment, or contrivance will comply with all of the following:

(1) All applicable orders, rules, and regulations of the district and of the state board.

(2) All applicable provisions of this division.

(c) Prohibit the issuance of a permit to a Title V source if the Administrator of the Environmental Protection Agency objects to its issuance in a timely manner

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as provided in Title V. This subdivision is not intended to provide any authority to the Environmental Protection Agency to object to the issuance of a permit other than that authority expressly granted by Title V.

(d) Provide that the air pollution control officer may issue to a Title V source a permit to operate or use if the owner or operator of the Title V source presents a variance exempting the owner or operator from Section 41701, any rule or regulation of the district, or any permit condition imposed pursuant to this section, or presents an abatement order that has the effect of a variance and that meets all of the requirements of this part pertaining to variances, and the requirements for the issuance of permits to operate are otherwise satisfied. The issuance of any variance or abatement order is a matter of state law and procedure only and does not amend a Title V permit in any way. Those terms and conditions of any variance or abatement order that prescribe a compliance schedule may be incorporated into the permit consistent with Title V and this division.

(e) Require, upon annual renewal, that each permit be reviewed to determine that the permit conditions are adequate to ensure compliance with, and the enforceability of, district rules and regulations applicable to the article, machine, equipment, or contrivance for which the permit was issued which were in effect at the time the permit was issued or modified, or which have subsequently been adopted and made retroactively applicable to an existing article, machine, equipment, or contrivance, by the district board and, if the permit conditions are not consistent, require that the permit be revised to specify the permit conditions in accordance with all applicable rules and regulations.

(f) Provide for the reissuance or transfer of a permit to a new owner or operator of an article, machine, equipment, or contrivance. An application for transfer of ownership only, or change in operator only, of any article, machine, equipment, or contrivance which had a valid permit to operate within the two-year period immediately preceding the application is a temporary permit to operate. Issuance of the final permit to operate shall be conditional upon a determination by the district that the criteria specified in subdivisions (b) and (e) are met, if the permit was not surrendered as a condition to receiving emission reduction credits pursuant to banking or permitting rules of the district. However, under no circumstances shall the criteria specify that a change of ownership or operator alone is a basis for requiring more stringent emission controls or operating conditions than would otherwise apply to the article, machine, equipment, or contrivance.

42303 INFORMATION DISCLOSURE

An air pollution control officer, at any time, may require from an applicant for, or the holder of, any permit provided for by the regulations of the district board, such information, analyses, plans, or specifications which will disclose the nature, extent, quantity, or degree of air contaminants which are, or may be, discharged by the source for which the permit was issued or applied.

42303.5 FALSE STATEMENTS

No person shall knowingly make any false statement in any application for a permit, or in any information, analyses, plans, or specifications submitted in conjunction with the application or at the request of the air pollution control officer.

42304 FAILURE TO SUPPLY INFORMATION

If, within a reasonable time, the holder of any permit issued by a district board willfully fails and refuses to furnish the information, analyses, plans, or specifications requested by the district air pollution control officer, such officer may suspend the permit. Such officer shall serve notice in writing of such suspension and the reasons therefor on the permittee.

42350 APPLICATIONS FOR VARIANCE

(a) Any person may apply to the hearing board for a variance from Section 41701 or from the rules and regulations of the district.

(b) (1) If the district board has established a permit system by regulation pursuant to Section 42300, a variance, or an abatement order which has the effect of a variance, may not be granted from the requirement for a permit to build, erect, alter, or replace.

(2) Title V sources shall not be granted a variance, or an abatement order which has the effect of a variance, from the requirement for a permit to operate or use.

(3) In districts with emission-capped trading programs, no variance shall be granted from the emission cap requirement.

42351 INTERIM VARIANCE APPLICATIONS

(a) Any person who has submitted an application for a variance and who desires to commence or continue operation pending the decision of the hearing board on the application, may submit an application for an interim variance.

(b) An interim variance may be granted for good causes stated in the order granting such a variance. The interim variance shall not be valid beyond the date of decision of the hearing board on the application of the variance or for more than 90 days from date of issuance of the interim variance, whichever occurs first.

(c) The hearing board shall not grant any interim variance (1) after it has held a hearing in compliance with the requirements of Section 40826, or (2) which is being sought to avoid the notice and hearing requirements of Section 40826.

42351.5 INTERIM SCHEDULE MODIFICATION

If a person granted a variance with a schedule of increments of progress files an application for modification of the schedule and is unable to notify the hearing board sufficiently in advance to allow the hearing board to schedule a public hearing on the application, the hearing board may grant no more than one interim authorization valid for not more than 30 days, to that person to continue operation pending the decision of the hearing board on the application. In districts with a population of less than 750,000, the chairman of the hearing board or any other member designated by the board may hear the application. If any member of the public contests such a decision made by a single member of the hearing board, the application shall be reheard by the full hearing board within 10 days of the decision. The interim authorization shall not be granted for a requested extension of a final compliance date or where the original variance expressly required advance application for the modification of an increment of progress.

42352 VARIANCE ISSUANCE REQUIREMENTS

(a) No variance shall be granted unless the hearing board makes all of the following findings:

(1) That the petitioner for a variance is, or will be, in violation of Section 41701 or of any rule, regulation, or order of the district.

(2) That, due to conditions beyond the reasonable control of the petitioner, requiring compliance would result in either (A) an arbitrary or unreasonable taking of property, or (B) the practical closing and elimination of a lawful business. In making those findings where the petitioner is a public agency, the hearing board shall consider whether or not requiring immediate compliance would impose an unreasonable burden upon an essential public service. For purposes of this paragraph, "essential public service" means a prison, detention facility, police or firefighting facility, school, health care facility, landfill gas control or processing facility, sewage treatment works, or water delivery operation, if owned and operated by a public agency.

(3) That the closing or taking would be without a corresponding benefit in reducing air contaminants.

(4) That the applicant for the variance has given consideration to curtailing operations of the source in lieu of obtaining a variance.

(5) During the period the variance is in effect, that the applicant will reduce excess emissions to the maximum extent feasible.

(6) During the period the variance is in effect, that the applicant will monitor or otherwise quantify emission levels from the source, if requested to do so by the district, and report these emission levels to the district pursuant to a schedule established by the district.

(b) As used in this section, "public agency" means any state agency, board, or commission, any county, city and county, city, regional agency, public district, or other political subdivision.

42353 OTHER REQUIREMENTS

Upon making the specific findings set forth in Section 42352, the hearing board shall prescribe requirements other than those imposed by statute or by any rule, regulation, or order of the district board, not more onerous, applicable to plants and equipment operated by specified industry or business or for specified activity, or to the operations of individual persons. However, no variance shall be granted if the operator, under the variance, will result in a violation of Section 41700.

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42354 PRESCRIBING REQUIREMENTS

In prescribing other and different requirements, in accordance with Section 42353, the hearing board, insofar as is consonant with the Legislature's declarations in Sections 39000 and 39001, shall exercise a wide discretion in weighing the equities involved and the advantages to the residents of the district from the reduction of air contaminants and the disadvantages to any otherwise lawful business, occupation, or activity involved, resulting from requiring compliance with such requirements.

42355 HEARING BOARD BOND REQUIREMENTS

(a) The hearing board may require, as a condition of granting a variance, that a bond be posted by the party to whom the variance was granted to assure performance of any construction, alteration, repair, or other work required by the terms and conditions of the variance. The bond may provide that, if the party granted the variance fails to perform the work by the agreed date, the bond shall be forfeited to the district having jurisdiction, or the sureties shall have the option of promptly remedying the variance default or paying to the district an amount, up to the amount specified in the bond, that is necessary to accomplish the work specified as a condition of the variance.

(b) The provisions of this section do not apply to vessels so long as the vessels are not operating in violation of any federal law enacted for the purpose of controlling emissions from combustion of vessel fuels.

42356 HEARING BOARD VARIANCE MODIFICATION

The hearing board may modify or revoke, by written order, any order permitting a variance.

42357 HEARING BOARD REVIEW OF SCHEDULE

The hearing board may review and for good cause, such as a change in the availability of materials, equipment, or adequate technology, modify a schedule of increments of progress or a final compliance date in such a schedule.

42358 EFFECTIVE PERIOD OF ORDER

(a) The hearing board, in making any order permitting a variance, shall specify the time during which such order shall be effective, in no event, except as otherwise provided in subdivision (b), to exceed one year, and shall set a final compliance date.

(b) A variance may be issued for a period exceeding one year if the variance includes a schedule of increments of progress specifying a final compliance date by which the emissions of air contaminants of a source for which the variance is granted will be brought into compliance with applicable emission standards.

42359 PUBLIC HEARING REQUIREMENTS

Except in the case of an emergency, as determined by the hearing board, the hearing board shall hold a hearing pursuant to Chapter 8 (commencing with Section 40800) of Part 3 to determine under what conditions, and to what extent, a variance shall be granted.

42359.5 EMERGENCY VARIANCES

(a) Notwithstanding any other provision of this article or of Article 2 (commencing with Section 40820) of Chapter 8 of Part 3, the Chairman of a district hearing board, or any other member of the hearing board designated thereby, may issue, without notice and hearing, an emergency variance to an applicant.

(b) An emergency variance may be issued for good cause, including, but not limited to, a breakdown condition. The district board in consultation with its air pollution control officer and the hearing board may adopt rules and regulations, not inconsistent with this subdivision, to further specify the conditions, and to what extent, an emergency variance may be granted.

The emergency variance shall not remain in effect longer than 30 days and shall not be granted when sought to avoid the provisions of Section 40824 or 42351.

42360 COPY OF VARIANCE ORDER TO ARB

Within 30 days of any order granting, modifying, or otherwise affecting a variance by the hearing board, or a member thereof pursuant to Section

42359.5, either the air pollution control officer or the hearing board shall submit a copy of the order to the state board.

42361 VALIDITY OF VARIANCE TIME

Any variance granted by the hearing board of a county district or a unified district, or any member of such a hearing board pursuant to Section 42359.5, applicable in an area which subsequently becomes included within a regional district, including the bay district, shall remain valid for the time specified therein or for one year, whichever is shorter, or, unless prior to the expiration of such time, the hearing board of the regional district modifies or revokes the variance.

42362 VARIANCE REVOCATION OR MODIFICATION

The state board may revoke or modify any variance granted by any district if, in its judgement, the variance does not require compliance with a required schedule of increments of progress or emission standards as expeditiously as practicable, or the variance does not meet the requirements of this article.

42363 ARB HEARING PRIOR TO ACTION

Prior to revoking or modifying a variance pursuant to Section 42362, the state board shall conduct a hearing pursuant to Chapter 8 (commencing with Section 40800) of Part 3 on the matter. The person to whom the variance was granted shall be given immediate notice of any such hearing by the hearing board, and shall be afforded an opportunity to appear at the hearing, to call and examine witnesses, and to otherwise partake as if he were a party to the hearing.

42364 SCHEDULE OF FEES

(a) The district board may adopt, by regulation, a schedule of fees which will yield a sum not exceeding the estimated cost of the administration of this article and for the filing of applications for variances or to revoke or modify variances. All applicants shall pay the fees required by the schedule, including, notwithstanding the provisions of Section 6103 of the Government Code, an applicant that is a publicly owned public utility.

(b) All such fees shall be paid to the district treasurer to the credit of the district.

42400 GENERAL VIOLATIONS, CRIMINAL

(a) Except as otherwise provided in Section 42400.1, 42400.2, or 42400.3, or 42400.4 who violates this part, or any rule, regulation, permit, or order of the state board or of a district, including a district hearing board, adopted pursuant to Part 1 (commencing with Section 39000) to Part 4 (commencing with Section 41500), inclusive, is guilty of a misdemeanor and is subject to a fine of not more than one thousand dollars ($1,000) or imprisonment in the county jail for not more than six months, or both.

(b) If a violation under subdivision (a) with regard to the failure to operate a vapor recovery system on a gasoline cargo tank is directly caused by the actions of an employee under the supervision of, or of any independent contractor working for, any person subject to this part, the employee or independent contractor, as the case may be, causing the violation is guilty of a misdemeanor and is punishable as provided in subdivision (a). That liability shall not extend to the person employing the employee or retaining the independent contractor, unless that person is separately guilty of an action that violates this part.

(c) (1) Any person who knowingly violates any rule, regulation, permit, order, fee requirement, or filing requirement of the state board or of a district, including a district hearing board, that is adopted for the control of toxic air contaminants pursuant to Part 1 (commencing with Section 39000) to Part 4 (commencing with Section 41500), inclusive, and for which delegation or approval of implementation and enforcement authority has been obtained pursuant to subdivision (l) of Section 112 of the Clean Air Act (42 U.S.C. Sec. 7412(l)), or the regulations adopted pursuant thereto, is guilty of a misdemeanor and is subject to a fine of not more than ten thousand dollars ($10,000) or imprisonment in the county jail for not more than six months, or both.

(2) Any person who knowingly makes any false material statement, representation, or certification in any form or in any notice or report required by a rule or regulation adopted or permit issued for the control of toxic air contaminants pursuant to Part 1 (commencing with Section 39000) to Part 4 (commencing with Section 41500), inclusive, and for which delegation or approval of implementation and enforcement authority has been obtained pursuant to subdivision (l) of Section 112 of the Clean Air Act (42 U.S.C. Sec. 7412(l)), or the regulations adopted pursuant thereto, or who knowingly renders inaccurate any monitoring device required by that toxic air contaminant rule, regulation, or permit is guilty of a misdemeanor and is subject to a fine of not more than ten

thousand dollars ($10,000) or imprisonment in the county jail for not more than six months, or both.

(3) Paragraphs (1) and (2) apply only to violations that are not otherwise subject to a fine of ten thousand dollars ($10,000) or more pursuant to Section 42400.1, 42400.2, or 42400.3.

(d) The recovery of civil penalties pursuant to Section 42402, 42402.1, 42402.2, or 42402.3 precludes prosecution pursuant to this section for the same offense. When a district refers a violation to a prosecuting agency, the filing of a criminal complaint is grounds requiring the dismissal of any civil action brought pursuant to this article for the same offense.

(e) Each day during any portion of which a violation of subdivision (a) or (c) occurs is a separate offense.

42400.1 NEGLIGENCE, CRIMINAL

(a) Any person who negligently emits an air contaminant in violation of any provision of this part or any rule, regulation, permit, or order of the state board or of a district pertaining to emission regulations or limitations is guilty of a misdemeanor and is subject to a fine of not more than fifteen thousand dollars ($15,000) or imprisonment in the county jail for not more than nine months, or both.

(b) Any person who owns or operates any source of air contaminant in violation of Section 41700 which causes actual injury, as defined in paragraph (2) of subdivision (d) of Section 42400.2, to the health or safety of a considerable number of persons or the public is guilty of a misdemeanor and is punishable as provided in subdivision (a).

(c) Each day during any portion of which a violation occurs is a separate offense.

(d) The recovery of civil penalties pursuant to Section 42402, 42402.1, 42402.2, or 42402.3, precludes prosecution pursuant to this section for the same offense. When a district refers a violation to a prosecuting agency, the filing of a criminal complaint is grounds requiring the dismissal of any civil action brought pursuant to this article for the same offense.

42400.2 DOCUMENT FALSIFICATION, CRIMINAL

(a) Any person who emits an air contaminant in violation of any provision of this part, or any order, rule, regulation, or permit of the state board or of a district pertaining to emission regulations or limitations, and who knew of the emission and failed to take corrective action within a reasonable period of time under the circumstances, is guilty of a misdemeanor and is subject to a fine of not more than twenty-five thousand dollars ($25,000) or imprisonment in the county jail for not more than one year, or both.

(b) For purposes of this section, "corrective action" means the termination of the emission violation or the grant of a variance from the applicable order, rule, regulation, or permit pursuant to Article 2 (commencing with Section 42350). If a district regulation regarding process upsets or equipment breakdowns would allow continued operation of equipment which is emitting air contaminants in excess of allowable limits, compliance with that regulation is deemed to be corrective action.

(c) Any person who, knowingly and with intent to deceive, falsifies any document required to be kept pursuant to any provision of this part, or any rule, regulation, permit, notice to comply, or order of the state board or of a district, is guilty of a misdemeanor and is punishable as provided in subdivision (a).

(d) (1) Any person who owns or operates any source of air contaminants in violation of Section 41700 which causes actual injury to the health or safety of a considerable number of persons or the public, and who knew of the emission and failed to take corrective action within a reasonable period of time under the circumstances, is guilty of a misdemeanor and is punishable as provided in subdivision (a).

(2) As used in this subdivision, "actual injury" means any physical injury which, in the opinion of a licensed physician and surgeon, requires medical treatment involving more than a physical examination.

(e) Each day during any portion of which a violation occurs constitutes a separate offense.

(f) The recovery of civil penalties pursuant to Section 42402, 42402.1, 42402.2, or 42402.3 precludes prosecution pursuant to this section for the same offense. When a district refers a violation to a prosecuting agency, the filing of a criminal complaint is grounds requiring the dismissal of any civil action brought pursuant to this article for the same offense.

42400.3 WILLFULLY EMITTING AN AIR CONTAMINANT

(a) Any person who willfully and intentionally emits an air contaminant in violation of any provision of this part or any rule, regulation, permit, or order of the state board or of a district, pertaining to emission regulations or limitations is guilty of a misdemeanor and is subject to a fine of not more than fifty thousand dollars ($50,000) or imprisonment in the county jail for not more than one year, or both.

(b) The recovery of civil penalties pursuant to Section 42402, 42402.1, 42402.2 or 42402.3 precludes prosecution pursuant to this section for the same offense. When a district refers a violation to a prosecuting agency, the filing of a criminal complaint is grounds requiring the dismissal of any civil action brought pursuant to this article for the same offense. (c) Each day during any portion of which a violation occurs constitutes a separate offense.

42401 VIOLATING ORDER OF ABATEMENT, CIVIL

Any person who intentionally or negligently violates any order of abatement issued by a district pursuant to Section 42450, by a hearing board pursuant to Section 42451, or by the state board pursuant to Section 41505 is liable for a civil penalty of not more than twenty-five thousand dollars ($25,000) for each day in which the violation occurs.

42402 GENERAL VIOLATIONS, CIVIL

(a) Except as otherwise provided in subdivision (b) or in Section 42402.1, 42402.2, or 42402.3, any person who violates this part, any order issued pursuant to Section 42316, or any rule, regulation, permit, or order of a district, including a district hearing board, or of the state board issued pursuant to Part 1 (commencing with Section 39000) to Part 4 (commencing with Section 41500), inclusive, is strictly liable for a civil penalty of not more than one thousand dollars ($1,000).

(b) (1) Any person who violates any provision of this part, any order issued pursuant to Section 42316, or any rule, regulation, permit, or order of a district, including a district hearing board, or of the state board issued pursuant to Part 1 (commencing with Section 39000) to Part 4 (commencing with Section 41500), inclusive, is strictly liable for a civil penalty of not more than ten thousand dollars ($10,000).

(2) (A) If a civil penalty in excess of one thousand dollars ($1,000) for each day in which the violation occurs is sought, there is no liability under this subdivision if the person accused of the violation alleges by affirmative defense and establishes that the violation was caused by an act which was not the result of intentional or negligent conduct.

(B) Subparagraph (A) does not apply to a violation of federally enforceable requirements that occur at a Title V source in a district in which a Title V permit program has been fully approved.

(C) Subparagraph (A) does not apply to a person who is determined to have violated an annual facility emissions cap established pursuant to a market-based incentive program adopted by a district pursuant to subdivision (b) of Section 39616.

(c) Each day during any portion of which a violation occurs is a separate offense.

42402.1 NEGLIGENCE OR ACTUAL INJURY, CIVIL

(a) Any person who negligently emits an air contaminant in violation of this part or any rule, regulation, permit, or order of the state board or of a district pertaining to emission regulations or limitations is liable for a civil penalty of not more than fifteen thousand dollars ($15,000).

(b) Any person who owns or operates any source of air contaminants in violation of Section 41700 which causes actual injury, as defined in paragraph (2) of subdivision (d) of Section 42400.2, to the health or safety of a considerable number of persons or the public is liable for a civil penalty as provided in subdivision (a).

(c) Each day during any portion of which a violation occurs is a separate offense.

42402.2 DOCUMENT FALSIFICATION, CIVIL

(a) Any person who emits an air contaminant in violation of any provision of this part, or any order, rule, regulation, or permit of the state board or of a district pertaining to emission regulations or limitations, and who knew of the emission and failed to take corrective action, as defined in subdivision (b) of Section 42400.2, within a reasonable period of time under the circumstances, is liable for a civil penalty, of not more than twenty-five thousand dollars ($25,000).

(b) Any person who, knowingly and with intent to deceive, falsifies any document required to be kept pursuant to any provision of this part, or any rule, regulation, permit, or order of the state board or of a district, is subject to the same civil penalty as provided in subdivision (a).

(c) Any person who owns or operates any source of air contaminants in violation of Section 41700 which causes actual injury, as defined in paragraph (2) of subdivision (d) of Section 42400.2, to the health or safety of a considerable number of persons or the public, and who knew of the emission and failed to take corrective action, as defined in subdivision (b), of Section 42400.2, within a reasonable period of time under the circumstances, is subject to a civil penalty as provided in subdivision (a).

(d) Each day during any portion of which a violation occurs is a separate offense.

42402.3 CIVIL PENALTIES

Any person who willfully and intentionally emits an air contaminant in violation of any provision of this part or any order, permit, rule, or regulation of the state board, or of a district, pertaining to emission regulations or limitations, is liable for a civil penalty of not more than fifty thousand dollars ($50,000).

42402.5 ADMINISTRATIVE PENALTIES

In addition to any civil and criminal penalties prescribed under this article, a district may impose administrative civil penalties for a violation of this part, or any order, permit, rule, or regulation of the state board or of a district, including a district hearing board, adopted pursuant to Part 1 (commencing with Section 39000) to Part 4 (commencing with Section 41500), inclusive, if the district board has adopted rules and regulations specifying procedures for the imposition and amounts of these penalties. No administrative civil penalty levied pursuant to this section may exceed five hundred dollars ($500) for each violation. However, nothing in this section is intended to restrict the authority of a district to negotiate mutual settlements under any other penalty provisions of law which exceeds five hundred dollars ($500).

42403 RECOVERY OF CIVIL PENALTIES

(a) The civil penalties prescribed in Sections 39674, 42401, 42402, 42402.1, 42402.2, and 42402.3 shall be assessed and recovered in a civil action brought in the name of the people of the State of California by the Attorney General, by any district attorney, or by the attorney for any district in which the violation occurs in any court of competent jurisdiction.

(b) In determining the amount assessed, the court, or in reaching any settlement, the district, shall take into consideration all relevant circumstances, including, but not limited to, the following:

(1) The extent of harm caused by the violation.

(2) The nature and persistence of the violation.

(3) The length of time over which the violation occurs.

(4) The frequency of past violations.

(5) The record of maintenance.

(6) The unproven or innovative nature of the control equipment.

(7) Any action taken by the defendant, including the nature, extent, and time of response of the cleanup and construction undertaken, to mitigate the violation.

(8) The financial burden to the defendant.

42404.5 STATUTE OF LIMITATIONS FOR CIVIL ACTIONS

Any limitation of time applicable to actions brought pursuant to Section 42403 shall not commence to run until the offense has been discovered, or could reasonably have been discovered.

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42450 ORDERS OF ABATEMENT

The district board may, after notice and a hearing, issue an order for abatement whenever it finds that any person is constructing or operating any article, machine, equipment, or other contrivance without a permit required by this part, or is in violation of Section 41700 or 41701 or of any order, rule, or regulation prohibiting or limiting the discharge of air contaminants into the air.

In holding such a hearing, the district board shall be vested with all the powers and duties of the hearing board. Notice shall be given, and the hearing shall be held, pursuant to Chapter 8 (commencing with Section 40800) of Part 3.

42700 MONITORING DEVICES

(a) The Legislature hereby finds and declares that stationary sources of air pollution are known to emit significant amounts of pollutants into the air, but that existing sampling techniques are not sufficiently precise to permit accurate measurement. The Legislature further finds and declares that more accurate data will improve the design of strategies for the control of pollutants in the most cost-effective manner.

(b) The Legislature further finds and declares that public complaints about excessive emissions from stationary sources are difficult or impossible to evaluate in the absence of adequate means of monitoring emissions on a continuing basis. The Legislature further finds and declares that, although the state board and the districts are authorized under Sections 41511 and 42303 to require stationary sources of air contaminants to install and operate monitoring devices to measure and record continuously the emissions concentration and amount of any specified pollutant, many districts have failed to exercise that authority.

(c) The Legislature further finds and declares that all districts, especially the bay district, the districts located, in whole or part, within the South Coast Air Basin, and the San Diego County Air Pollution Control District, should be encouraged to require that monitoring devices be installed in each stationary source of air contaminants that emits into the atmosphere 100 tons or more each year of nonmethane hydrocarbons, oxides of nitrogen, oxides of sulfur, reduced sulfur compounds, or particulate matter or 1,000 tons or more each year of carbon monoxide.

(d) The Legislature further finds and declares that, pursuant to Section 39616, the south coast district has required the installation of a substantial number of monitoring devices and the installation and use of strip chart recorders for compliance purposes. However, electronic or computer data capture and storage is generally less costly and may have the capability to provide greater data availability with the same degree of security.

(e) To encourage the districts to take actions to monitor emissions of stationary sources as described in this section, the state board shall determine the availability, technological feasibility, and economic reasonableness of monitoring devices for those stationary sources as provided by Section 42701.

(f) To make emissions data available to the public and to minimize burdens on the private sector, the districts shall allow stationary sources the option of using electronic or computer data storage for purposes of compliance with Section 39616.

42701 AVAILABILITY, FEASIBILITY

(a) For the purposes of Sections 41511 and 42303, the state board shall determine the availability, technological feasibility, and economic reasonableness of monitoring devices to measure and record continuously the emissions concentration and amount of nonmethane hydrocarbons, oxides of nitrogen, oxides of sulfur, reduced sulfur compounds, particulate matter, and carbon monoxide emitted by stationary sources. Such determination shall be made for stationary sources which emit such contaminants in the quantities set forth in Section 42700, and may be made for stationary sources which emit lesser amounts. The state board shall complete an initial review of submitted devices by June 1, 1975.

42702 SPECIFICATION OF PROCESSES

The state board shall specify the types of stationary sources, processes, and the contaminants, or combinations thereof, for which a monitoring device is available, technologically feasible, and economically reasonable. Such specification may be by any technologically based classification, including on an industry-wide basis or by individual stationary source, by air basin, by district, or any other reasonable classification.

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42703 REIMBURSEMENTS FOR TESTING EXPENSES

The state board shall require the manufacturer of any monitoring device submitted for a determination to reimburse the state board for its actual expenses incurred in making the determination, including, where applicable, its contract expenses for testing and review.

42704 DETERMINATION OF AVAILABILITY

After the state board has made a determination of availability, the state board may, as appropriate, revoke or modify its prior determination of availability if circumstances beyond the control of the state board, or of a stationary source required to install a monitoring device, cause a substantial delay or impairment in the availability of the device or cause the device no longer to be available.

42705 RECORDS

Any stationary source required by the district in which the source is located to install and operate a monitoring device shall retain the records from the device for not less than two years and, upon request, shall make the records available to the state board and the district. The district shall allow the source the option of using electronic or computer data storage, as defined in Section 40407.5 and consistent with Section 40440.3, as a method of record retention. The source shall not be limited solely to the installation or maintenance of strip chart recorders.

42706 REPORT OF VIOLATION

Any violation of any emission standard to which the stationary source is required to conform, as indicated by the records of the monitoring device, shall be reported by the operator of the source to the district within 96 hours after such occurrence. The district shall, in turn, report the violation to the state board within five working days after receiving the report of the violation from the operator.

42707 INSPECTION; FEES

The air pollution control officer shall inspect, as he determines necessary, the monitoring devices installed in every stationary source of air contaminants located within his jurisdiction required to have such devices to insure that such devices are functioning properly. The district may require reasonable fees to be paid by the operator of any such source to cover the expense of such inspection and other costs related thereto.

42708 POWERS OF LOCAL OR REGIONAL AUTHORITY

This chapter shall not prevent any local or regional authority from adopting monitoring requirements more stringent than those set forth in this chapter or be construed as requiring the installation of monitoring devices on any stationary source or classes of stationary sources. This section shall not limit the authority of the state board to require the installation of monitoring devices pursuant to Chapter 1 (commencing with Section 41500).

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Latest Definitions of VOC and ROG - As Of April 14, 1998

1. U.S. EPA Definition of VOC (Volatile Organic Compounds):

The U.S. Environmental Protection Agency (U.S. EPA) defines and uses the term Volatile Organic Compounds (VOC). The term VOC is defined in the Federal Register. The original definition of VOC made reference to the vapor pressure of the compounds (greater than 0.1 millimeter of mercury) as a determinant of volatility. However, the current definition relies solely on a list of exempted compounds having "negligible photochemical reactivity".

U.S. EPA periodically exempts additional compounds. Proposed exemptions are pending. A summary follows.

RECENT FINAL RULEMAKINGS:

(1) Acetone was exempted by final rule published June 16, 1995 (60 FR 31633).

(2) Perchloroethylene was exempted by final rule published February 7, 1996 (61 FR 4588).

(3) In response to petitions, the U.S. EPA exempted HFC 43-10mee, HCFC 225ca, and HCFC 225cb. The final rule was published October 8, 1996 (61 FR 52848), and became effective November 7, 1996.

(4) The Alliance for Responsible Atmospheric Policy, Arlington, Virginia, petitioned to exempt 22 compounds, primarily HFCs and HCFCs, but later withdrew five of these. U.S. EPA exempted 16 of the 17 requested compounds (excluding HCFC-150a). The final rule was published August 25, 1997 (62 FR 44900), effective September 24, 1997.

(5) U.S. EPA exempted Methyl acetate, in response to petition from Eastman Chemical, April 9, 1998 (63 FR 17331).

PENDING RULEMAKINGS AND PETITIONS (as of April 14, 1998):

(6) According to Bill Johnson at U.S. EPA, OAQPS, the U.S. EPA is rethinking aspects of its reactivity policy, such as a molar vs. gram basis for reactivity. A national workshop is scheduled for May 12, 13, 14 in North Carolina.

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(7) U.S. EPA received petitions, which are pending review, requesting to exempt the following additional compounds:

Chlorobromomethane - from ICF Kaiser (SAI Division), San Rafael, California (11/95);

1-Bromopropane - from EnviroTech International, Alameda, California (5/96);

Methyl bromide - from Chemical Manufacturers Association, Wash ington, D.C. (7/96);

N-Alkanes (C_{12} - C_{18}) - from The Aluminum Association, Washington, D.C. (11/96);

Technical white oils - from The Printing Industries of America and Pennzoil Products Company (12/96);

t-Butyl acetate - from ARCO Chemical Company (1/97);

Benzotrifluoride - from Occidental Chemical Company, Niagara Falls, NY (3/97);

Carbonyl sulfide - from E.I. du Pont de Nemours and Company (8/97).

trans-1,2-Dichloroethylene - from 3M Corporation, St. Paul, MN (10/97).

Dimethyl succinate and Dimethyl glutarate - from the Dibasic Esters Group, affiliated with the Synthetic Organic Chemical Manu facturers Association, Inc. (10/97).

Carbon disulfide - Texas Mid-Continent Oil and Gas Association (12/97)

Acetonitrile - BP Chemicals and GNI Chemicals Corporation (12/98)

Toluene diisocyanate - Chemical Manufacturers Association (1/98)

HFC-227ea - Great Lakes Chemical Corporation (2/98)

(U.S. EPA also previously received inquiries about methanol and isopropanol.)

The complete federal definition and the list of exempted compounds to date are shown on the following pages.

Prepared April 1998 by Beth Schwehr, California Air Resources Board, Technical Support Division, Emission Inventory Analysis Section. For questions, call (916) 322-6002.

U.S. EPA Definition of VOC (as of April 14, 1998): (based on final rules to date)

40 CFR Part 51 Section 51.100 Definitions.

(s) **Volatile organic compounds (VOC)** means any compound of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate, which participates in atmospheric photochemical reactions.

(1) This includes any such organic compound other than the following, which have been determined to have negligible photochemical reactivity:

methane;	[74-82-8]*
ethane;	[74-84-0]
methylene chloride (dichloromethane);	[75-09-2]
1,1,1-trichloroethane (methyl chloroform);	[71-55-6]
1,1,2-trichloro-1,2,2-trifluoroethane (CFC-113);	[76-13-1]
trichlorofluoromethane (CFC-11);	[75-69-4]
dichlorodifluoromethane (CFC-12);	[75-43-4]
chlorodifluoromethane (HCFC-22);	[75-45-6]
trifluoromethane (HFC-23);	[75-46-7]
1,2-dichloro-1,1,2,2-tetrafluoroethane (CFC-114);	[76-14-2]
chloropentafluoroethane (CFC-115);	[76-15-3]
1,1,1-trifluoro-2,2-dichloroethane (HCFC-123);	[306-83-2]
1,1,1,2-tetrafluoroethane (HFC-134a);	[811-97-2]
1,1-dichloro-1-fluoroethane (HCFC-141b);	[1717-00-6]
1-chloro-1,1-difluoroethane (HCFC-142b);	[75-68-3]
2-chloro-1,1,1,2-tetrafluoroethane (HCFC-124);	[2837-89-0]
pentafluoroethane (HFC-125);	[354-33-6]
1,1,2,2-tetrafluoroethane (HFC-134);	[359-35-3]
1,1,1-trifluoroethane (HFC-143a);	[420-46-2]
1,1-difluoroethane (HFC-152a);	[75-37-6]
parachlorobenzotrifluoride (PCBTF);	[98-56-6]
cyclic, branched, or linear completely methylated siloxanes;	[various]
acetone;	[67-64-1]
perchloroethylene (tetrachloroethylene);	[127-18-4]
3,3-dichloro-1,1,1,2,2-pentafluoropropane (HCFC-225ca);	[422-56-0]
1,3-dichloro-1,1,2,2,3-pentafluoropropane (HCFC-225cb);	[507-55-1]
1,1,1,2,3,4,4,5,5,5-decafluoropentane (HFC-43-10mee);	[138495-42-8]
difluoromethane (HFC-32);	[75-10-5]
ethylfluoride (HFC-161);	[353-36-6]
1,1,1,3,3,3-hexafluoropropane (HFC-236fa);	[690-39-1]
1,1,2,2,3-pentafluoropropane (HFC-245ca);	[679-86-7]
1,1,2,3,3-pentafluoropropane (HFC-245ea);	[24270-66-4]
1,1,1,2,3-pentafluoropropane (HFC-245eb);	[431-31-2]
1,1,1,3,3-pentafluoropropane (HFC-245fa);	[460-73-1]
1,1,1,2,3,3-hexafluoropropane (HFC-236ea);	[431-63-0]
1,1,1,3,3-pentafluorobutane (HFC-365mfc);	[406-58-6]
chlorofluoromethane (HCFC-31);	[593-70-4]
1-chloro-1-fluoroethane (HCFC-151a);	[1615-75-4]
1,2-dichloro-1,1,2-trifluoroethane (HCFC-123a);	[354-23-4]
1,1,1,2,2,3,3,4,4-nonafluoro-4-methoxy-butane ($C_4F_9OCH_3$);	[163702-07-6]
2-(difluoromethoxymethyl)-1,1,1,2,3,3,3-heptafluoropropane ($(CF_3)_2CFCF_2OCH_3$);	[163702-08-7]
1-ethoxy-1,1,2,2,3,3,4,4,4-nonafluorobutane ($C_4F_9OC_2H_5$);	[163702-05-4]

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2-(ethoxydifluoromethyl)-1,1,1,2,3,3,3-heptafluoropropane ($(CF_3)_2CFCF_2OC_2H_5$); [163702-06-5]

methyl acetate [79-20-9]

and perfluorocarbon compounds which fall into these classes: [various]

(i) Cyclic, branched, or linear, completely fluorinated alkanes;
(ii) Cyclic, branched, or linear, completely fluorinated ethers with no unsaturations;
(iii) Cyclic, branched, or linear, completely fluorinated tertiary amines with no unsaturations; and
(iv) Sulfur containing perfluorocarbons with no unsaturations and with sulfur bonds only to carbon and fluorine.

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* NOTE: Chemical Abstract Service (CAS) identification numbers have been included in brackets [ ] for convenience.

2. California Air Resources Board's Definition of ROG (Reactive Organic Gases):

The California Air Resources Board's (ARB's) Emission Inventory Branch (EIB) uses the terms Total Organic Gases (TOG) and Reactive Organic Gases (ROG). California air pollution control districts report Total Organic Gases (TOG) to the Air Resources Board's emission inventory.

For each source category, the ARB derives a value for the Reactive Organic Gases (ROG) by multiplying the reported TOG by the Fraction of Reactive Organic Gases (FROG). Each source category is keyed to one of some 200 available chemical speciation profiles. For each category, the FROG value is calculated as the weight fraction of those species designated by the ARB as reactive in the speciation profile applicable to the category. The ARB's organic gas speciation profiles are reported in the document Identification of Volatile Organic Compound Species Profiles: ARB Speciation Manual, Second Edition, Volume 1 of 2, August 1991.

The relationships among these organic gas terms are summarized as follows:

TOG (Total Organic Gas)	-	**Exempt cmpds** (ARB list of methane, CFCs, etc.)	=	**ROG** (Reactive Organic Gas)
TOG (Total Organic Gas)	x	**FROG** (Fraction of Reactive Organic Gas)	=	**ROG** (Reactive Organic Gas)

The Air Pollution Emission Inventory Program manual, ARB, March 1982, listed the compounds which the ARB initially treated as exempted from ROG. The list differed somewhat from the U.S. EPA's list of exempted VOCs even at the time, in that ARB's definition of ROG did not exempt Ethane. As discussed in the prior section, U.S. EPA later exempted additional compounds from the federal definition of VOC as well.

Subsequently, the Air Resources Board was petitioned regarding exemptions from the ARB's regulations. The ARB staff formed a Reactive Organic Gas Technical Committee (ROGTC), made up of staff from the ARB's affected

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divisions and district representatives, to systematically evaluate the proposed exemption of these compounds. At a public hearing in September 1995, the Air Resources Board took action to revise the definition of Volatile Organic Compounds in the consumer products regulations, based on the recommendations of the ROGTC. Methyl siloxanes were added to the list of exempted compounds, and parachlorobenzotrifluoride, acetone, and ethane were added to the list of exempted compounds with the qualifier that they are "low-reactive organic compounds which have been exempted by the U.S. EPA". Based on the ROGTC's analysis, the staff similarly modified the overall inventory definition of ROG to extend the Board's action on the consumer products regulations to all inventory applications.

The Air Resources Board exempted Perchloroethylene from the definition of VOC in the Consumer Products regulations in November 1996. Perchloroethylene is under evaluation for other inventory categories.

The complete definitions and the list of exempted compounds to date are shown on the following pages.

ARB's Definitions of TOG and ROG (as of April 14, 1998):

Total Organic Gases (TOG) means compounds of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate.

Reactive Organic Gases (ROG) means any compound of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate, and excluding the following:

(1) methane;	[74-82-8]*
methylene chloride (dichloromethane);	[75-09-2]
1,1,1-trichloroethane (methyl chloroform);	[71-55-6]
trichlorofluoromethane (CFC-11);	[75-69-4]
dichlorodifluoromethane (CFC-12);	[75-43-4]
1,1,2-trichloro-1,2,2-trifluoroethane (CFC-113);	[76-13-1]
1,2-dichloro-1,1,2,2-tetrafluoroethane (CFC-114);	[76-14-2]
chloropentafluoroethane (CFC-115);	[76-15-3]
chlorodifluoromethane (HCFC-22);	[75-45-6]
1,1,1-trifluoro-2,2-dichloroethane (HCFC-123);	[306-83-2]
2-chloro-1,1,1,2-tetrafluoroethane (HCFC-124);	[2837-89-0]
1,1-dichloro-1-fluoroethane (HCFC-141b);	[1717-00-6]
1-chloro-1,1-difluoroethane (HCFC-142b);	[75-68-3]
trifluoromethane (HFC-23);	[75-46-7]
pentafluoroethane (HFC-125);	[354-33-6]
1,1,2,2-tetrafluoroethane (HFC-134);	[359-35-3]
1,1,1,2-tetrafluoroethane (HFC-134a);	[811-97-2]
1,1,1-trifluoroethane (HFC-143a);	[420-46-2]
1,1-difluoroethane (HFC-152a);	[75-37-6]
cyclic, branched, or linear completely methylated siloxanes;	[various]
the following classes of perfluorocarbons:	[various]

(A) cyclic, branched, or linear, completely fluorinated alkanes;
(B) cyclic, branched, or linear, completely fluorinated ethers with no unsaturations;
(C) cyclic, branched, or linear, completely fluorinated tertiary amines with no unsaturations; and
(D) sulfur-containing perfluorocarbons with no unsaturations and with the sulfur bonds only to carbon and fluorine; and

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(2) the following low-reactive organic compounds which have been exempted by the U.S. EPA:

acetone;	[67-64-1]
ethane;	[74-84-0]
[perchloroethylene]**; and	[127-18-4]
parachlorobenzotrifluoride (1-chloro-4-trifluoromethyl benzene).	[98-56-6]

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* NOTE: Chemical Abstract Service (CAS) identification numbers have been included in brackets [ ] for convenience.

** The Air Resources Board exempted Perchloroethylene from the definition of VOC in the Consumer Products regulations in November 1996. Perchloroethylene is under evaluation for other inventory categories.

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